RESEARCH REPORT No. 63-66

# ULTRASONIC WELDING

# OF REFRACTORY METALS AND ALLOYS

# WITH POWER-FORCE PROGRAMMING

by
Nicholas Maropis
John G. Thomas

## FINAL REPORT

December, 1963

Prepared under Navy, Bureau of Naval Weapons

Contract NOw 63-0125-c

## AEROPROJECTS INCORPORATED
### WEST CHESTER, PENNSYLVANIA

Submitted to
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Washington 25, D.C.

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FOREWORD

This report on the ultrasonic welding of refractory metals was prepared by Aeroprojects Incorporated, West Chester, Pennsylvania, under Navy Contract NOw 63-0125-c. Mr. R. M. Gustafson of the Materials Division, Bureau of Naval Weapons, Department of the Navy, provided liaison and technical assistance. The Contract was administered through the Inspector of Naval Material, Reading, Pennsylvania.

The investigations reported herein constitute a continuation of the work performed by Aeroprojects Incorporated under Navy Contract NOw 61-0410-c and summarized in Research Report No. 63-64, "Ultrasonic Welding of Selected Refractory Metals and Alloys," dated June 1963.

The literature survey on refractory metal properties and their effects on ultrasonic weldability included as Appendix A was conducted by J. Koziarski.

# ULTRASONIC WELDING OF REFRACTORY METALS AND ALLOYS
# WITH POWER-FORCE PROGRAMMING

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Aeroprojects Incorporated

## ABSTRACT

Equipment was assembled for ultrasonic welding with power-force pro-
gramming, to provide incremental changes in ultrasonic power and clamping
force during a single weld interval. Preliminary welding of 2024-T3 alu-
minum alloy and Inconel X-750 showed significant weld strength improvement
with power-force programming, which was selected without extensive experi-
mentation. Significantly improved weld strengths and lower strength vari-
ability were obtained with power-force programmed welding of 0.010-inch
and 0.013-inch molybdenum-0.5% titanium alloy and with 0.015-inch B-66
niobium alloy.

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# I. INTRODUCTION

Ultrasonic welding offers a means for joining refractory metals and alloys without some of the disadvantages of conventional welding techniques which involve melting. When such metals are melted during joining, the cast structure of the fusion zone and the recrystallization, grain growth, and preferential precipitation of impurities in the heat-affected zone contribute to embrittlement of the joint.

With ultrasonic welding, which is a solid-state process, no melting takes place and brittle cast structures are not formed. A temperature rise does occur with the introduction of high-frequency vibratory energy, but it is extremely localized and transient and does not approach the melting point of the metal, and it need not achieve recrystallization temperatures. Bonding occurs rather through the effect of combined static and alternating stresses which disperse surface films and lead to nascent metal contact and various degrees of mutual interpenetration of the metal surfaces.

Various high-temperature, high-strength metals and alloys, such as the precipitation-hardened steels, high-strength nickel alloys, and others, have been effectively joined in thin gages by ultrasonic welding. Some success has also been achieved with refractory metals, including molybdenum, niobium, and tungsten and their alloys. However, welding machine settings requisite to producing high-quality welds appeared to be more critical than for the more common metals and alloys, and often required readjustment to accommodate variations in material quality.

From the results of prior experimental work, it was anticipated that more reproducible, good-quality bonds in the refractory metals and alloys could be obtained with the use of power-force programming during ultrasonic welding, i.e., with incremental variations in ultrasonic power and in static clamping force during the weld cycle.

This report describes the evolution of ultrasonic welding with power-force programming and its application to the welding of molybdenum-0.5% titanium, B-66 niobium alloy, and tungsten.

## A. ACCOMPLISHMENTS UNDER PREVIOUS PROGRAM

Effort to weld selected refractory metals ultrasonically was undertaken under the earlier Contract NOw 61-0410-c (1).* This work encompassed thin gages (from 0.005 inch to approximately 0.020 inch) of molybdenum-0.5% titanium alloy, niobium-10% molybdenum-10% titanium (D-31) alloy, and tungsten.

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*Numbers in parentheses refer to References on page 83.

These materials showed good metallurgical susceptibility to ultrasonic welding, with various degrees of plastic flow and mutual interpenetration at the interfaces. Tests of tensile-shear specimens at 2000°F showed no preferential degradation of weld strengths over the base metal strengths.

However, consistently sound, crack-free welds were not attainable with all the materials used on the program. These materials came from odd lots and exhibited considerable variation in physical and mechanical properties. Welding machine settings had to be readjusted for each lot of material. Cracking in or adjacent to the weld zone proved to be a problem, particularly with the molybdenum alloy. These cracking tendencies appeared to be related to the surface contamination of the material, which in some instances, as determined by recrystallization studies, extended through almost the entire metal thickness.

A short weld interval, approximately 0.5 second or less, at high power was found more effective than a longer cycle at lower power. Some success was achieved with the use of a foil interleaf of titanium or tantalum between the surfaces being joined. It also appeared that preheating of the weld metal prior to the introduction of vibratory energy favorably affected the weldability of these materials.

A promising solution, however, appeared to be the use of power-force programming during the welding cycle. Manually applied power programming had been used briefly in the welding of tungsten and also in beryllium welding, using equipment which provided opportunity for two or three incremental changes in power during the weld cycle. Weld strength using this apparatus was increased and strength variability decreased. The technique thus showed promise for improving the quality of ultrasonic welds in the refractory metals.


B.  RATIONALE FOR POWER-FORCE PROGRAMMING

In past work, for the most part, ultrasonic spot-type welding has been carried out with single preset values of power and clamping force, and these values have been experimentally established for particular materials and material thicknesses. Standing-wave-ratio measurements, which provide an indication of the actual acoustic power delivered to the weld zone at any instant during the weld cycle (3,4), have revealed a variation in delivered power during weld formation under constant power and force settings. At the initiation of the weld cycle, there is an induction period during which some slippage of the welding tip occurs in establishing coupling to the weldment. During this period, vibratory energy is inefficiently utilized and actual power delivery may be low, but increasing. This is followed by an interval during which power delivery is substantially higher. Toward the end of the cycle, the delivered power gradually declines.

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On this basis it was postulated that the weld cycle could be initiated with a low power pulse which would serve to "couple" the welding tip to the work and also to preheat the weld metal before the alternating high stresses associated with full power delivery are introduced. The low power pulse could then be followed by an increase in power to form the weld. The improved weld quality obtained by such an increase in power was evidenced by previous results obtained with tungsten and beryllium.

Since the interaction between power and clamping force is important in controlling power delivery* and in producing good welds, concurrent variations in the clamping force were required. For example, the initial coupling between tip and work might be facilitated by a high clamping force, which could subsequently be alleviated to provide less restraint to the vibratory excursion of the tip during actual weld formation.

## C. OBJECTIVES OF THE INVESTIGATIONS

The current work was undertaken to investigate the ultrasonic welding of the refractory metals and alloys with the application of power-force programming (PFP) during the weld cycle.

The initial work involved modification of an existing power programming design to provide for ten incremental power values and ten incremental force values within a single weld cycle, and the incorporation of this modified system on an existing 4-kilowatt ultrasonic spot-type welder.

The PFP system was evaluated first with materials of known ultrasonic weldability, such as stainless steel and high nickel alloys, followed by more comprehensive experimentation with molybdenum-0.5% titanium alloy and preliminary evaluation with tungsten and with a niobium alloy. Welds were evaluated by metallography and by tensile-shear tests. The experiments were statistically designed and the results statistically analyzed to provide a basis for evaluating the effectiveness of welding with power-force programming.

This report describes the development and installation of power-force programming equipment, the experimental work performed, the materials used, and the results obtained.

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*This relationship is discussed in detail in Refs. (3) and (4).

## II. EXPERIMENTAL MATERIALS

### A. NON-REFRACTORY MATERIALS

Preliminary evaluation of power-force programming was carried out with several non-refractory alloys of known ultrasonic weldability: 2024-T3 bare aluminum alloy in thicknesses of 0.040, 0.050, and 0.063 inch, 0.031-inch AISI 304 stainless steel, and 0.016-inch Inconel X-750. Machine settings for obtaining sound, high-strength ultrasonic welds in these materials under unprogrammed conditions of power and clamping force were available.

### B. REFRACTORY MATERIALS

The refractory metals were similar to those used in the previous program (1): molybdenum-0.5% titanium alloy, a niobium alloy, and tungsten. The niobium alloy, however, was changed from that previously used. The D-31 alloy (niobium-10% molybdenum-10% titanium) was replaced by a niobium alloy of reportedly superior properties. The alloy used was B-66, which has a composition of 5% molybdenum, 5% vanadium, 1% zirconium, balance niobium.

Since the earlier work clearly indicated the importance of material quality, effort was made to procure each of the three materials in the highest quality obtainable. Where possible, certified test reports containing detailed chemical and physical analyses of the specific materials procured were obtained from the manufacturers.

Properties for the molybdenum and niobium alloys, where known, are presented in Table I, along with the properties for pure tungsten.

A survey of available information on these materials was made, particularly regarding metallurgical properties, and the effects of these properties on weldability in general and ultrasonic weldability in particular. Results of this work are discussed in Appendix A, wherein it is indicated that although available information is not altogether complete and is sometimes contradictory, the welding difficulties with these refractory metals appear to stem from several factors. The brittle-to-ductile transition temperature is significant. The presence of contaminants, which, in the case of the molybdenum alloy for example, may consist of interstitial oxygen, nitrogen, and carbon, can degrade room-temperature ductility and increase the transition temperature, contributing to brittleness and weld cracking. The rolled sheet may have a fibrous character, leading to delamination under the ultrasonic welding forces. These considerations emphasized the importance of high-quality stress-relieved material with a minimum of contamination and fibrous structure. These factors affect not only ultrasonic welding but other welding processes as well.

Table I

AVAILABLE PERTINENT PROPERTIES OF REFRACTORY METALS

| Property | Unit | Molybdenum-0.5% Titanium (5-7) | B-66 Alloy (Niobium) (8) | Tungsten (9-10) |
|---|---|---|---|---|
| Density | g/cc | 10.2 | 8.44 | 19.3 |
| Melting Point | $^{\circ}$C | 2620 | 2371 | 3410 |
| | $^{\circ}$F | 4750 | 4300 | 6170 |
| Crystal Structure | | bcc | bcc | bcc |
| Specific Heat | cal/g/$^{\circ}$C (20$^{\circ}$C) | 0.061 | 0.065[*] | 0.032 |
| Thermal Conductivity | cal/cm$^2$/cm/$^{\circ}$C/sec (20$^{\circ}$C) | 0.35 | 0.125[*] | 0.397 |
| Coefficient of Linear Thermal Expansion | cm/cm/$^{\circ}$C (20$\circ$C) | $5.5 \times 10^{-6}$ | $7.42 \times 10^{-6}$[**] | $4.98 \times 10^{-6}$ |
| Modulus of Elasticity | psi | $46 \times 10^6$ | $14.6 \times 10^6$ | $50 \times 10^6$ |
| Recrystallization Temperature (1 hour in vacuum) | $^{\circ}$C | 900 (min) | 1205 (0.005" foil) 1371 (0.016" sheet) | 1100 (min) |

[*]Properties for pure niobium; alloy properties not available.

[**]At 25$^{\circ}$C; coefficient at 20$^{\circ}$C not available.

1.  Molybdenum-0.5% Titanium Alloy

New molybdenum-0.5% titanium alloy was obtained in gages of 0.005 inch, 0.010 inch, and 0.020 inch, and in addition, residual material 0.013 inch thick from Lot 2 of the previous investigation was used. The new material was designated as Lots 5 through 7 to distinguish these lots from those previously used. Available information on the processing history and chemical and physical properties is presented in Table II. The properties of Lots 5 and 6, provided in the manufacturer's certified test reports, showed less variation than that supplied for the earlier work. The material of both lots was stress-relieved. No information was available for the 0.020-inch gage except for microhardness measurements made after receipt of the material.

The 0.013-inch alloy had originally been procured in the 0.015-inch gage. However, this had previously been chemically etched to remove surface contaminants by immersion for 4 minutes in a solution of 95% sulfuric acid (95% by weight), 70% nitric acid (4.5%), 48% hydrofluoric acid (0.5%), and chromic anhydride (18.8 grams per liter); the thickness was thus reduced to approximately 0.013 inch.

2.  B-66 Niobium Alloy

The B-66 niobium alloy was obtained in the recrystallized condition in gages of 0.005 inch and 0.015 inch. Only the 0.015-inch material was welded during the course of this program. A certified test report was provided with this material, and the physical property data included therein are presented in Table III. This certified report also provided the following fabrication history of the material:

a.  Alloy was double electron-beam melted and double-arc remelted into an 8-inch-diameter ingot.

b.  Conditioned ingot was extruded to 3 by 6 inch sheet bar.

c.  Conditioned and sectioned sheet bar was vacuum-annealed at 1650°C.

d.  Sheet bar was forged to a slab of dimensions 1-1/2 by 9 by 20 inches.

e.  Slab was vacuum annealed at 1550°C.

f.  Vacuum-annealed slab was forged to 3/4 by 15 by 20 inch plate.

g.  Conditioned plate was warm rolled to 0.125-inch-thick sheet.

Table II

PROPERTIES OF VARIOUS LOTS AND GAGES
OF MOLYBDENUM-0.5% TITANIUM ALLOY
USED ON THE PROGRAM

| | Description | Gage, inch | Composition | Ultimate Tensile Strength, psi | | Yield Strength, psi | | Elongation, percent | | Hardness,* DPH |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Longitudinal | Transverse | Longitudinal | Transverse | Longitudinal | Transverse | |
| LOT 5 | Stress relieved at 1075°C for 1 hour, 98% cold worked | 0.005 | 0.020 C 0.46 Ti | 146,500 to 147,500 | | 149,400 to 147,900 | | 12.0 10.0 | | |
| LOT 6 | Stress relieved at 1075°C for 1 hour, 95% cold worked | 0.010 | 0.020 C 0.46 Ti | 138,300 | | 145,500 | | 11.0 | | 319 |
| LOT 7 | | 0.020 | | | | | | | | 412 |
| LOT 2** | Vacuum arc cast, hot rolled, stress relieved, descaled by manufacturer at 0.015 inch gage | 0.015 (etched to 0.013) | 0.48 Ti 0.022 C | 137,700 to 139,000 | 123,000 to 133,600 | 102,800 to 105,200 | 101,600 to 102,600 | 10-12 | 13 | 302.8 |

*Measured at Aeroprojects; all other properties from manufacturer's certification (General Electric Co., Lamp Materials and Components Div., Ingot T6788B2, July 9, 1963).

**Material from previous program; etching done at Aeroprojects.

Table III

PROPERTIES OF B-66 NIOBIUM ALLOY

|  | Lot 1 | Lot 2 |
|---|---|---|
| Description | Recrystallized | Recrystallized |
| Gage, Inch | 0.005 | 0.015 |
| Composition | 4.68% Mo, 4.53% V, 0.94% Zr, 143 ppm O, 112 ppm N, 51 ppm C | Same |
| **Room Temperature Properties** | | |
| Ultimate Tensile Strength, psi | | |
| Longitudinal | | 98,500 |
| Transverse | | 101,500 |
| Yield Strength, psi | | |
| Longitudinal | | 72,000 |
| Transverse | | 73,500 |
| Elongation, percent | | |
| Longitudinal | | 28 |
| Transverse | | 28 |
| Hardness, DPH* | | 229 |
| **Properties at 2400°F** | | |
| Ultimate Tensile Strength, psi | | |
| Longitudinal | | 20,800 |
| Transverse | | 20,800 |
| Yield Strength, psi | | |
| Longitudinal | | 17,000 |
| Transverse | | 18,000 |
| Elongation, percent | | |
| Longitudinal | | 58 |
| Transverse | | 86 |

*Measured at Aeroprojects; all other properties are from manufacturer's certified test report (Westinghouse Electric Corporation, Materials Manufacturing Division, June 13, 1963).

h. Sheet was vacuum-annealed at 1375°C.

i. Vacuum-annealed sheet was warm-rolled to 0.050-inch-thick sheet.

j. 0.050-inch-thick sheet was cold-rolled to 0.015-inch-thick sheet.

k. 0.015-inch-thick sheet was vacuum-annealed at 1375°C.

3. Tungsten

Three lots of 0.010-inch tungsten were available for use on the program, as noted in Table IV. That designated as Lot 6 had been manufactured under the Department of Defense Refractory Metal Sheet Rolling Program and was reportedly of superior quality, although composition and property data were not available. For the material in Lot 7, a spectrographic analysis of the chemical composition was supplied. Lot 2 consisted of material residual from the previous program.

Table IV

PROPERTIES OF VARIOUS LOTS OF TUNGSTEN

| | Lot 6 | Lot 7 | Lot 2 |
|---|---|---|---|
| Description | Refractory Metal Sheet Rolling Program | General Electric Alloy 6061B | Residual From Previous Program |
| Sheet Gage, Inch | 0.010 | 0.010 | 0.010 |
| Chemical Composition | | Al, Ca, Cr, Cu, Fe, K, Mg, Mn, Na, Ni, Si, Sn--each $< 0.001$; Mo $< 0.002$, Balance W | |
| Hardness, DPH* | 566 | 660 | 552 |

*Measured at Aeroprojects.

## III. EXPERIMENTAL EQUIPMENT

### A. ULTRASONIC WELDING EQUIPMENT

The ultrasonic welding equipment was a laboratory-type 4-kilowatt spot-type welder suitably modified for power-force programming. The basic welder (Figure 1) incorporates magnetostrictive transducers for converting high-frequency electrical energy to mechanical vibratory energy, a wedge-reed-type coupling system terminating in a welding tip for delivering this energy to the weld zone, an anvil for supporting the workpieces, a hydraulic system for applying clamping force to the weldment, and a timer for controlling the duration of the weld cycle. The transducers were driven by a 4-kilowatt electronic power source which generated the necessary electrical current at a nominal frequency of 15 kilocycles per second.

The transducers were laminated nickel stacks, each 2.25 by 2.25 by 5.8 inches, and each wound with an r-f excitation coil to apply the necessary high-frequency excitation current, and also a polarization coil carrying a d-c current and producing a magnetic bias on the transducer.

In the wedge-reed-type coupling system, longitudinal vibration transmitted from the transducer into the wedge induces flexural vibration in the mass-supported reed to effect shear-type vibration in the weld zone of the materials being joined. Clamping force is applied through the mass-reed components, and the anvil provides the necessary reaction for both the axial static and the dynamic shear stresses associated with ultrasonic welding. As a result of the previously reported investigations of welding tip materials (1), welding tips and anvil faces were fabricated of the nickel-base alloy Udimet 700. For joining the refractory metals, the welding tip radius was 3/4 inch except in the case of the 0.020-inch material, for which the radius was increased to 1.0 inch. These selections are consistent with the contractor's experience that best welds are obtained with tip radii in the range of about 50 to 100 times the thickness of the sheet against the radiused tip. The anvil face was flat.

### B. MODIFICATIONS FOR POWER-FORCE PROGRAMMING

The 4-kilowatt ultrasonic welder was modified to incorporate power-force programming circuitry and appropriate control instrumentation so that power and clamping force could each be varied in ten increments during the weld interval. The following components were added to the standard machine:

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1.  A peg-board-type master control panel,

2.  Transistorized variable delay relays for the time-base
    control circuit,

3.  Function control relays for directing the signals for
    power and control,

4.  A servo-amplifier,

5.  A feedback pressure transducer, and

6.  A servo-valve for force control.

The complete assembly of equipment, together with various recording devices
used in evaluation of the system, is shown in Figure 2.

The peg-board-type control panel, shown in Figure 3, provided a matrix
system of ten increments for setting levels of power and force along the
ordinate and ten increments in the selected weld interval along the abscissa,
which always represents the total value of the weld interval as set on the
master interval timer. Decimal-step variation of power and force could thus
be obtained over any portion of the weld interval.

At the outset, consideration was given to the rate of response to incre-
mental variations that would be required of the power-force programming
circuitry. The requirements shown in Table V were set out initially, and the
various components were selected to meet these requirements.

1.  Power Programming System

In a standard welder driven by an electronic power source, the power
output is controlled by varying the level of the high-frequency signal applied
to the power stages of the power source. Measurements have shown that the
output power follows variations in the amplitude of the applied signal, and
that the response time, from the instant the control signal is applied until
the output power is actually changed, is less than 0.002 second. Therefore
a conventional step-variable control of the signal level was incorporated to
provide control of applied welding power.

In order to provide this step control, resistors in the output of
the oscillator controlling the power source were coupled to power control relays
in the power-force programming circuit. This system was found to operate satis-
factorily and provided the desired level of response to meet the requirements
shown in Table V.

13
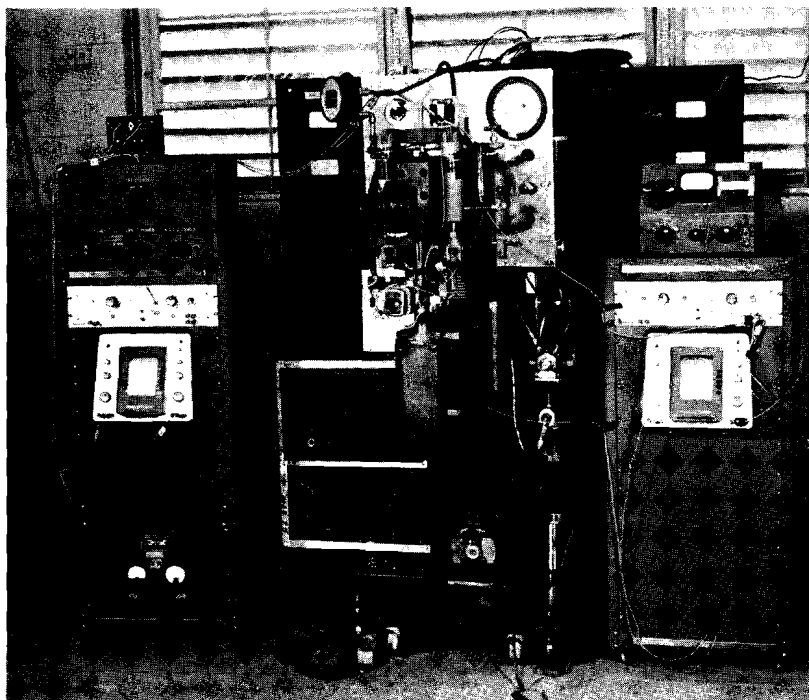
Figure 2

4-KILOWATT ULTRASONIC WELDER WITH EXPERIMENTAL POWER-FORCE
CONTROLS AND ASSOCIATED RECORDING INSTRUMENTATION
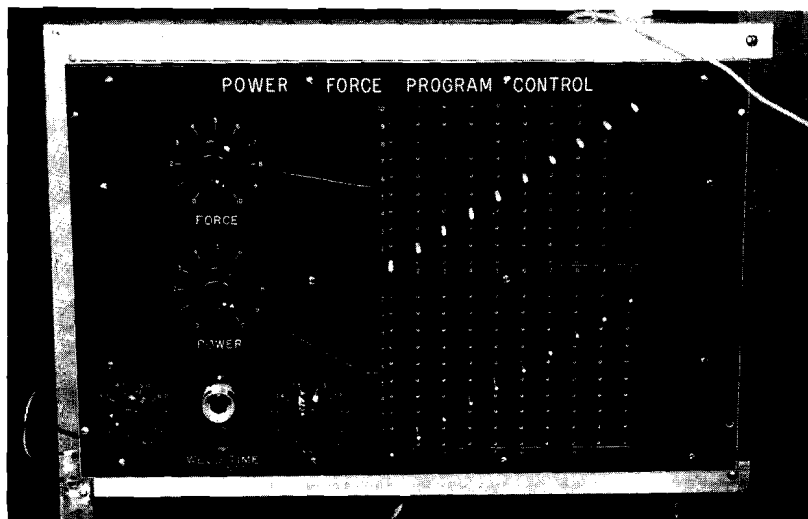


Figure 3

POWER-FORCE PROGRAM CONTROL PANEL SET FOR
PROGRESSIVE INCREASES OF EACH PARAMETER

TABLE V

REQUIREMENTS FOR POWER-FORCE PROGRAMMING CIRCUIT

| Program Component | Response Time, seconds |
|---|---|
| Time Base (Step-type time control, ten steps for total weld times of 0-5 seconds) | |
| Response Through Control Relays | 0.005 |
| Power Control | |
| Electronic Power Source Only | 0.005* |
| Force Control | |
| Hydraulic (Servo-Valve or Parallel By-pass Solenoids) | |
| Rise | 0.050 |
| Decay | 0.030 |

*Permits use of standard relays.

2. Force Programming System

In standard ultrasonic welders with hydraulic force systems, the clamping force is controlled by adjustment of the pressure of the hydraulic oil acting in the force cylinder. This system is shown by the solid lines in Figure 4.

To provide the rapid force change required for the force programming, it was necessary to provide a variable orifice to increase or decrease the oil pressure delivered by the motor and hydraulic pump (Z), at a point beyond the manually adjustable pressure valve (Q). Several types of control systems were evaluated to determine their response characteristics: a solenoid-controlled tapered-seat-type valve, a solenoid-controlled high-response shear-seal valve, and a servo valve. Results of this evaluation, shown in Figure 5, showed the servo valve and associated servo amplifier to be superior, and this system was selected. In addition, a feedback transducer installed at the force cylinder provided a signal which was constantly referenced to the command signal to maintain the desired pre-selected clamping force. The dotted lines in Figure 4 show the circuitry added to the system.

3. Monitoring Instrumentation

Three types of sensing and recording systems were assembled to monitor the operation of the power-force programming array in terms of actual power delivered to the transducer, actual clamping force delivered through the sonotrode, and displacement of the welding tip. These systems are represented in the block diagrams of Figure 6.

Power was monitored by sampling the control signal from a resistive divider, applying it to an amplifier-rectifier unit, and recording the signal on a strip-chart recorder.

The SR-4 strain gages used for measuring force were mounted on the hydraulic cylinder. These strain gages were shielded to avoid extraneous pickup noise from the magnetic field associated with the nickel transducers. The signal from the gages was fed through a strain analyzer circuit and recorded on a strip-chart oscillograph.

To measure tip displacement, a ceramic phonograph cartridge and stylus assembly (Astatic Corporation No. 51-2) was shock-mounted on the welder with the stylus in contact with the welding tip. The output voltage of the cartridge was related to tip displacement by a calibration against simultaneous microscopic measurements of tip displacement while welding aluminum over the machine power range. The magnitude of the output signal was proportional to the displacement, and was amplified and recorded on a strip-chart instrument in the same manner as power and force.

16
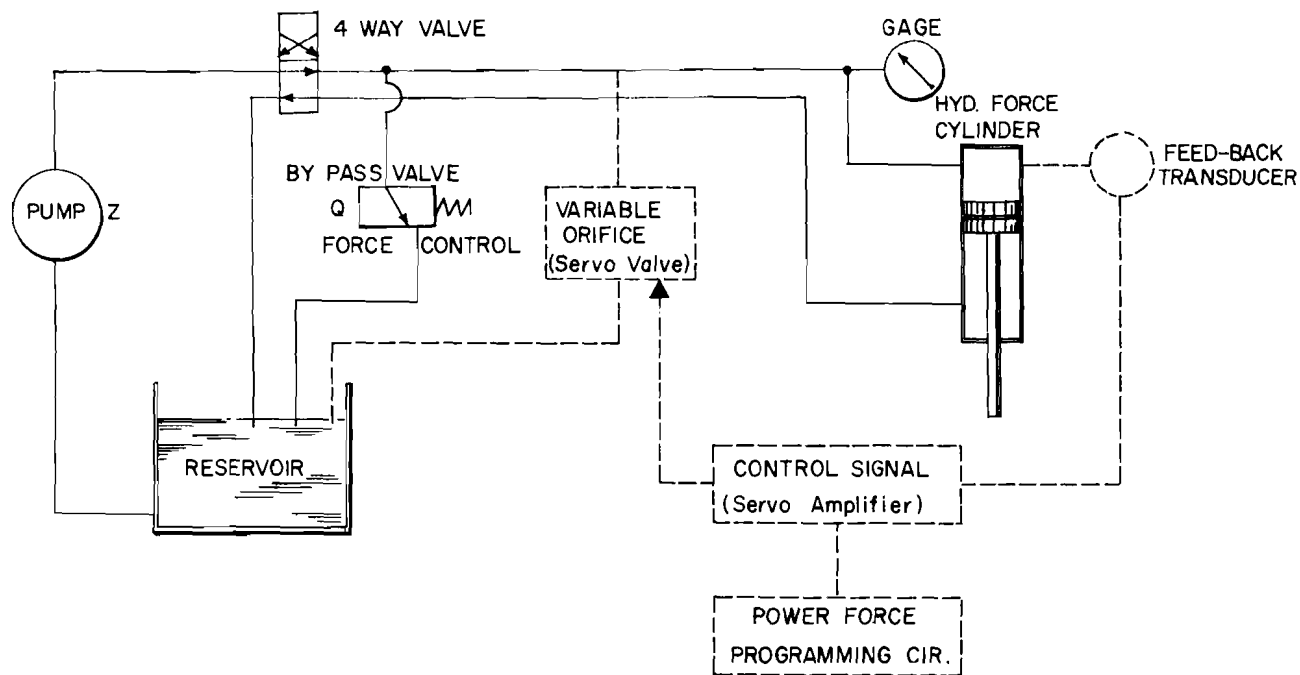
Figure 4

HYDRAULIC CIRCUIT FOR STANDARD ULTRASONIC WELDER (SOLID LINES)
AND CIRCUITRY INSTALLED FOR FORCE PROGRAMMING (DOTTED LINES)
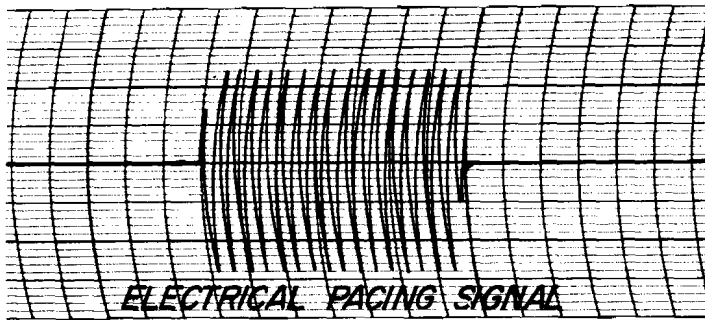
**A  RESPONSE CURVE TO SINGLE-STEP CONTROL AND 60-CYCLE PACING SIGNAL (SHEAR-SEAL VALVE)**
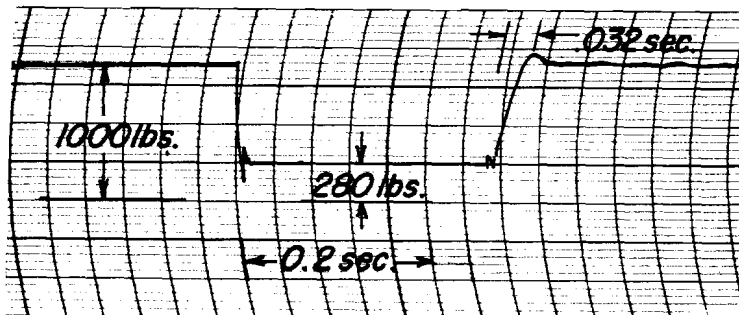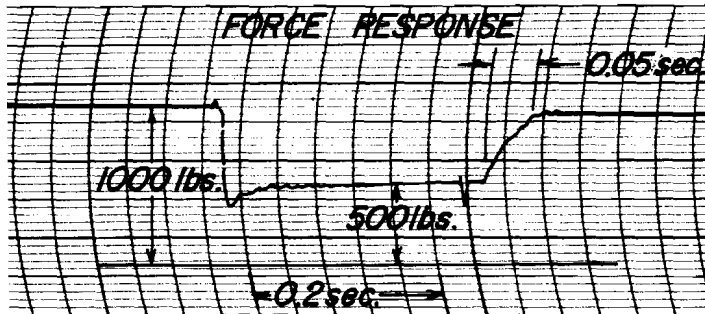
**B  RESPONSE CURVE TO SINGLE-STEP CONTROL (SERVO VALVE)**

**C  FORCE RESPONSE CURVES**

A:  Solenoid-Controlled Tapered-Seat-Type Valve

B:  Solenoid-Controlled High-Response Shear-Seal Valve

C:  Addition of Low Pressure Ball-Check Valve in Control Line

D:  Estimated Response with Addition of Pressure Accumulator

E:  Response with Servo-Valve By-Pass Control
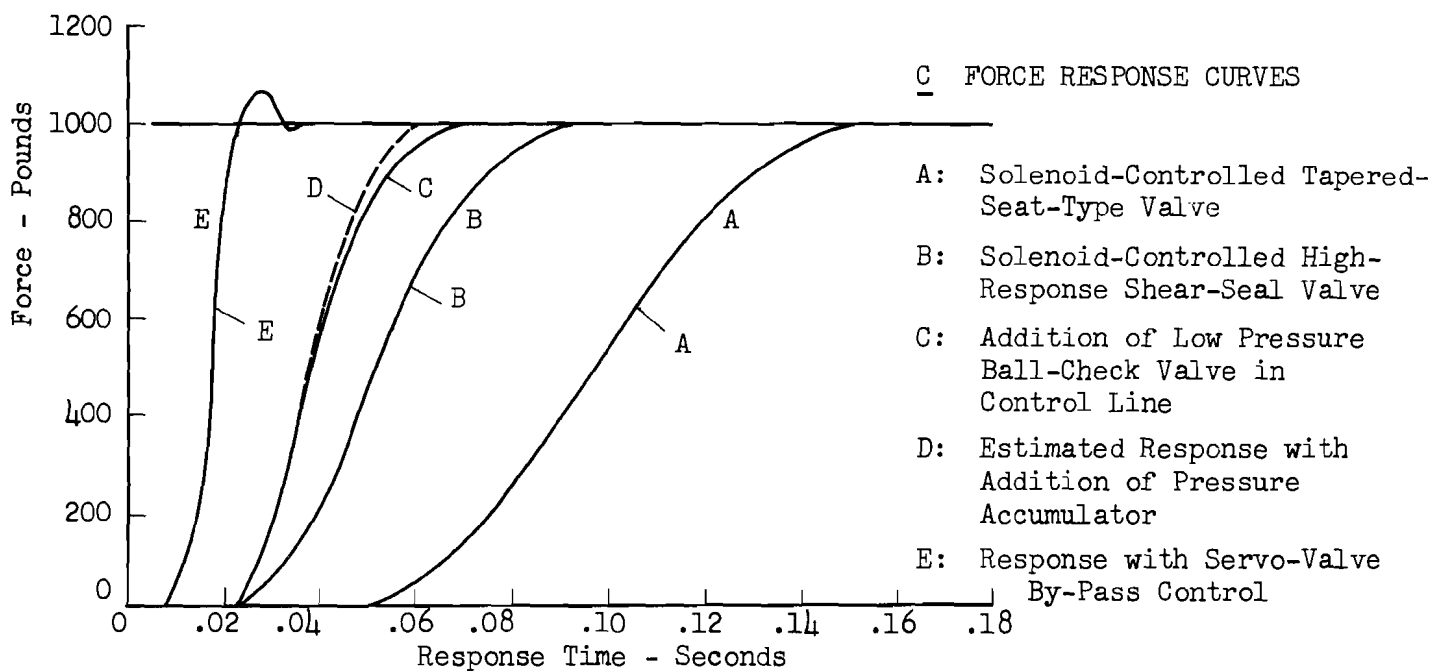
Figure 5

RESPONSE CURVES OBTAINED WITH THE TAPERED-SEAT, SHEAR-SEAL, AND SERVO VALVES

```
┌──────────────────┐   ┌──────────────────┐   ┌──────────────────┐
│      Power       │   │     Force        │   │  Displacement    │
│ Take-off from    │   │  SR-4 Strain     │   │  Phonograph      │
│   Resistive      │   │    Gages         │   │    Needle        │
│    Divider       │   │                  │   │                  │
└────────┬─────────┘   └────────┬─────────┘   └────────┬─────────┘
         │                      │                      │
         │                      │                      │
┌────────┴─────────┐   ┌────────┴─────────┐   ┌────────┴─────────┐
│    Amplifier     │   │   Brush-Type     │   │   Amplifier      │
│      and         │   │    Strain        │   │     and          │
│   Rectifier      │   │   Analyzer       │   │   Rectifier      │
└────────┬─────────┘   └────────┬─────────┘   └────────┬─────────┘
         │                      │                      │
         │                      │                      │
┌────────┴─────────┐   ┌────────┴─────────┐   ┌────────┴─────────┐
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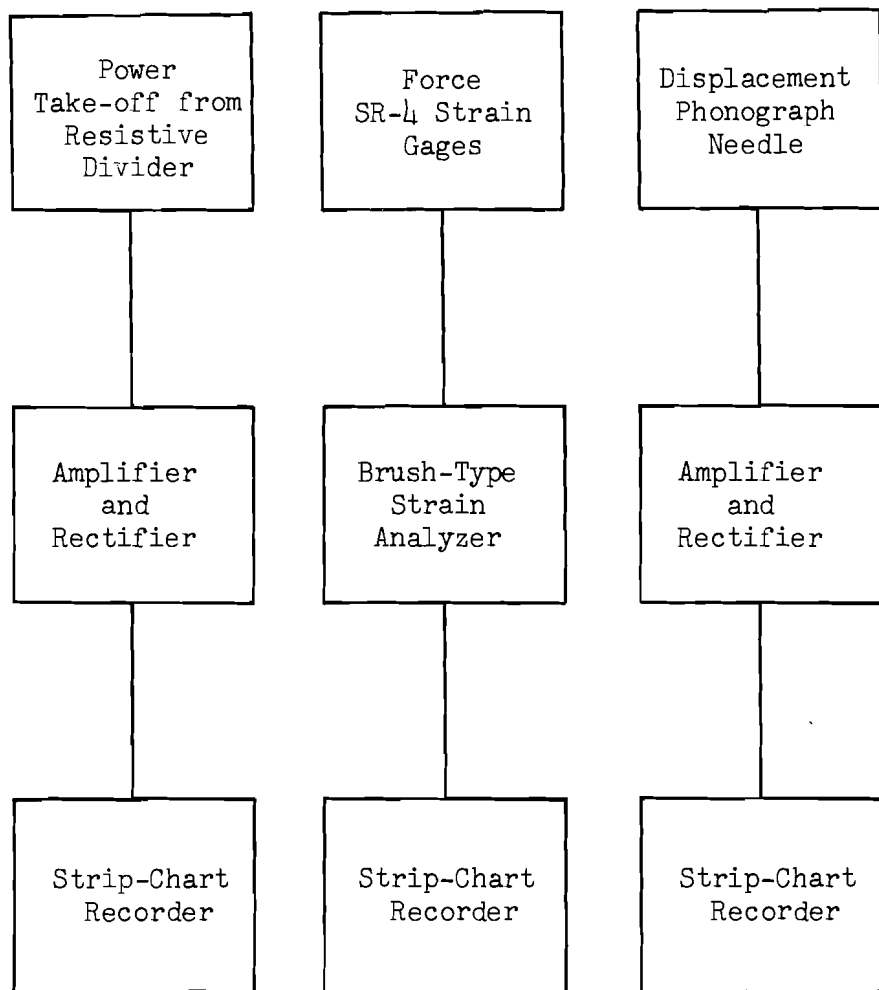
Figure 6

SCHEMATIC OF POWER-FORCE PROGRAMMING SYSTEM SENSING ELEMENTS
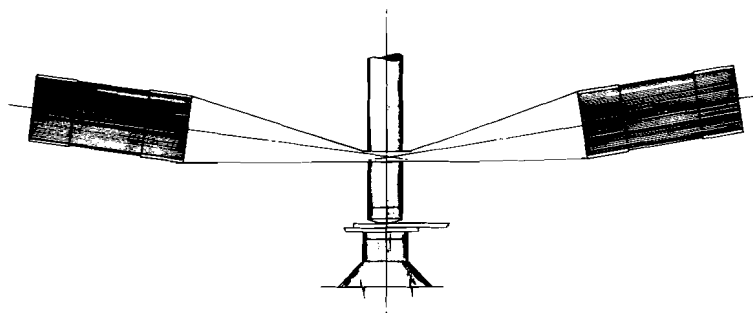
Figure 1

SCHEMATIC OF TRANSDUCER-COUPLING SYSTEM FOR

STANDARD 4-KILOWATT ULTRASONIC SPOT-TYPE WELDING MACHINE

For evaluation of the response of the power-force programming system, the control panel was set as shown in Figure 3 to provide ten successive incremental increases in both power and force. The recorded data, reproduced in Figure 7, indicated operation to be reasonably satisfactory.

## IV.  EXPERIMENTAL PROCEDURES

### A.  PREPARATION AND HANDLING OF MATERIALS

All weldment materials were inspected visually for pits, scratches, and cracks.  Little evidence of such surface damage was noticeable on the refractory metals obtained for this work.  Surface preparation consisted of degreasing the weld coupons in acetone.

A welding fixture, positioned with reference to the anvil, for supporting the specimens during welding, was utilized to assure that the two weld coupons being joined were accurately aligned and that the weld was located on the center line of the weldment.

### B.  WELDING MACHINE SETTINGS

To provide a base for determining power and force values for PFP welding, approximate welding machine settings of power, clamping force, and weld time for standard non-programmed ultrasonic welding, i.e., welding with constant power and constant force, were determined.  In some instances such data were available from previous work.  Several techniques were used to establish these settings for the remaining materials.  The values for all materials are summarized in Table VI.

Prior to this work, considerable data had been accumulated in welding the non-refractory metals, 2024-T3 bare aluminum alloy, Type 304 stainless steel, and Inconel X-750, and suitable standard machine settings were thus available.

Similarly 0.010-inch molybdenum-0.5% titanium alloy had been welded previously (1), and it then appeared that good bonding could be produced at 700 pounds clamping force and a minimum energy of about 1200 watt-seconds.  A small number of specimens were welded at various power and force levels within the vicinity of these earlier settings, and the non-programmed machine settings were in the range of 700 pounds clamping force, 3000-3200 watts power, and 0.3 to 0.5 second weld time.(corresponding to energies ranging from 900 to 1600 watt-seconds).

For the 0.013-inch molybdenum alloy, the required energy was estimated using the previously developed weld energy equation, which is discussed in detail elsewhere (1,3,4):

$$E = K_e H^{3/2} t^{3/2},$$

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Table VI

STANDARD WELDING MACHINE SETTINGS FOR MATERIALS OF INTEREST

| Material | Sheet Gage, inch | Clamping Force, pounds | Power, watts | Weld Time, seconds | Weld Energy, watt-seconds | Tip Radius, inch |
|---|---|---|---|---|---|---|
| 2024-T3 Bare Aluminum | 0.040 | 800 | 2400 | 1.5 | 3600 | 3 |
| | 0.050 | 900 | 3600 | 1.5 | 5400 | 3 |
| | 0.063* | 1150 | 4200 | 1.5 | 6300 | 3 |
| Type 304 Stainless Steel | 0.031 | 550 | 3000 | 1.0 | 3000 | 3 |
| Inconel X-750 | 0.016 | 300 | 1800 | 1.0 | 1800 | 3 |
| Molybdenum-0.5% Titanium | 0.010 | 700 | 3000-3200 | 0.3-0.5 | 1000-1600 | 3/4 |
| | 0.013 | 700-750 | 3600 | 0.5 | 1800 | 3/4 |
| | 0.020** | 800 | 4200 | 1.5 | 6300 | 1 |
| B-66 Niobium Alloy | 0.015 | 850 | 3500 | 0.8 | 2800 | 3/4 |
| Tungsten | 0.010** | 850 | 4200 | 1.5 | 6300 | 3/4 |

*Welded with interleaf of 0.001-inch 1100-H18 aluminum.

**Welding was marginal due to insufficient power.

where E represents, to a first approximation, the electrical energy to the transducers required to weld, H is the Vickers microindentation hardness of the sheets being welded, t is the thickness of the sheet in contact with the welding tip, in inches, and $K_e$ is constant for the type of transducer-coupling system. For estimates of comparative energy among various materials welded by the same system, the ratio of energies may be determined. In calculations of energy ratio, the $K_e$ term will cancel. Since the 0.013-inch material has essentially the same hardness as the 0.010-inch sheet (see Table II), the difference in energy is approximately equal to the ratio of the relative thicknesses of the alloys to the 3/2 power:

$$\frac{E_{(0.013)}}{E_{(0.010)}} = \left(\frac{0.013}{0.010}\right)^{3/2} = 1.43.$$

On this basis the energy required to weld the 0.013-inch sheet was estimated at approximately 1700 watt-seconds. Experimentation established settings of 700-750 pounds clamping force, 3600 watts power, and 0.5 second weld time (1800 watt-seconds).

Similarly, the approximate energy required to weld the 0.020-inch molybdenum alloy was estimated from the weld energy equation. In this case the thicker material was substantially harder (VHN = 412 vs. 319), and this difference was also taken into consideration:

$$\frac{E_{(0.020)}}{E_{(0.010)}} = \left(\frac{0.020}{0.010}\right)^{3/2} \left(\frac{412}{319}\right)^{3/2} = 4.15,$$

giving a minimum weld energy requirement of about 5000 watt-seconds. To develop this energy with a 4-kilowatt welding machine would necessitate a weld time of about 1.25 seconds. This is probably too long, since high powers and short weld times have experimentally been found necessary for sound welds, particularly for the refractory metals (1).

In order to establish an optimum clamping force, the threshold curves of Figure 8 were constructed from experimental data, using a previously established technique (1,3,4). These curves were constructed from joints representing the lowest power values for which joining was possible for a given clamping force. The welds were made at weld times of 0.5 and 0.8 second, and the indicated power levels were too low to provide strong bonds. The curves, however, confirm
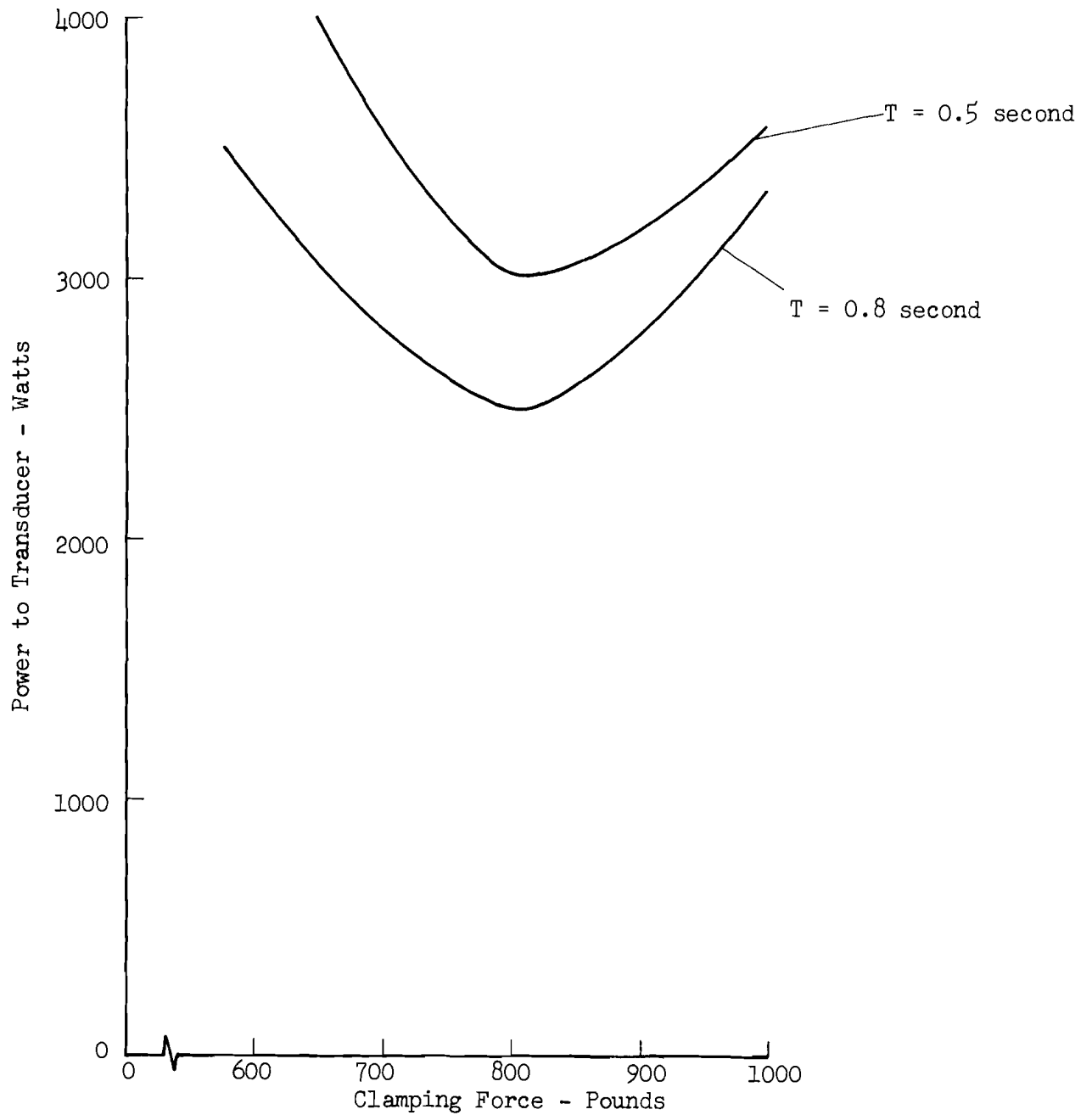
Figure 8

THRESHOLD CURVES OF POWER AT TWO WELD INTERVALS
FOR 0.020-INCH MOLYBDENUM-0.5% TITANIUM ALLOY

a satisfactory clamping force of approximately 800 pounds. After some experimentation using the maximum power of the welding machine (4200 watts), a weld time of 1.5 seconds was selected for non-programmed welding of this material.

The approximate minimum energy required to weld the 0.015-inch B-66 niobium alloy was estimated from the energy equation previously described to be 2600 watt-seconds. Clamping force was determined, by the threshold technique, to be in the range of 800-850 pounds (Figure 9). The standard settings selected for this material were therefore 850 pounds clamping force, 3500 watts power, and 0.8 second weld time.

The 0.010-inch tungsten was estimated, from the energy equation, to require 4650 watt-seconds of energy, which is beyond the capacity of the welding machine for weld times of less than 1 second. Scouting experiments were carried out over a range of weld times, using maximum welder power. The conditions which were required for bonding were 850 pounds clamping force, 4200 watts power, and 1.5 seconds weld time. It was recognized that, to achieve sound welds in this material, a reduction in weld time would be required. This would be possible only with the use of higher-powered welders.

## C. POWER-FORCE PROGRAM PATTERNS

The power-force programs were selected from consideration of the properties of the refractory metals as they affect weldability, as well as consideration of phenomena associated with ultrasonic welding.

It is basic to the process that a good impedance match be obtained between the sonotrode tip and the materials being welded. This has not been obtained in the initial portion of the weld cycle with constant power and force, as evidenced by observed tip slippage and by the character of previously obtained tip displacement curves (1). Accordingly, during the induction period the power and clamping force should be varied so as to shorten the induction period. Clamping force might be increased at the outset to minimize slippage. Power might either be held constant or initiated at a reduced value, depending upon the clamping force situation. Later in the weld cycle, after coupling is accomplished, both power and clamping force can be adjusted to values considered requisite for good welding, in order to accomplish the actual bonding.

It was further postulated that power and associated vibratory stresses could be kept initially low in order to elevate material temperature to above the brittle-ductile transition level before application of higher power.

Accordingly, the four power-force programs shown in Figure 10 were investigated. Pattern A represents standard welding conditions in which power and force are held constant throughout the weld interval; B provides increased
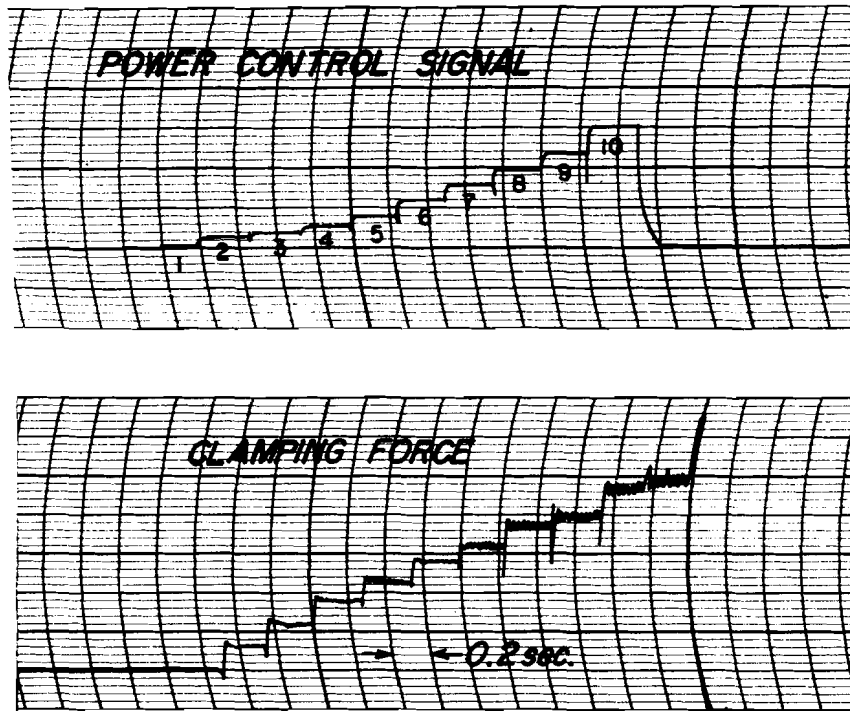
Figure 7

RECORDED POWER CONTROL SIGNAL AND RECORDED
CLAMPING FORCE FOR
PROGRESSIVE INCREASES OF EACH PARAMETER
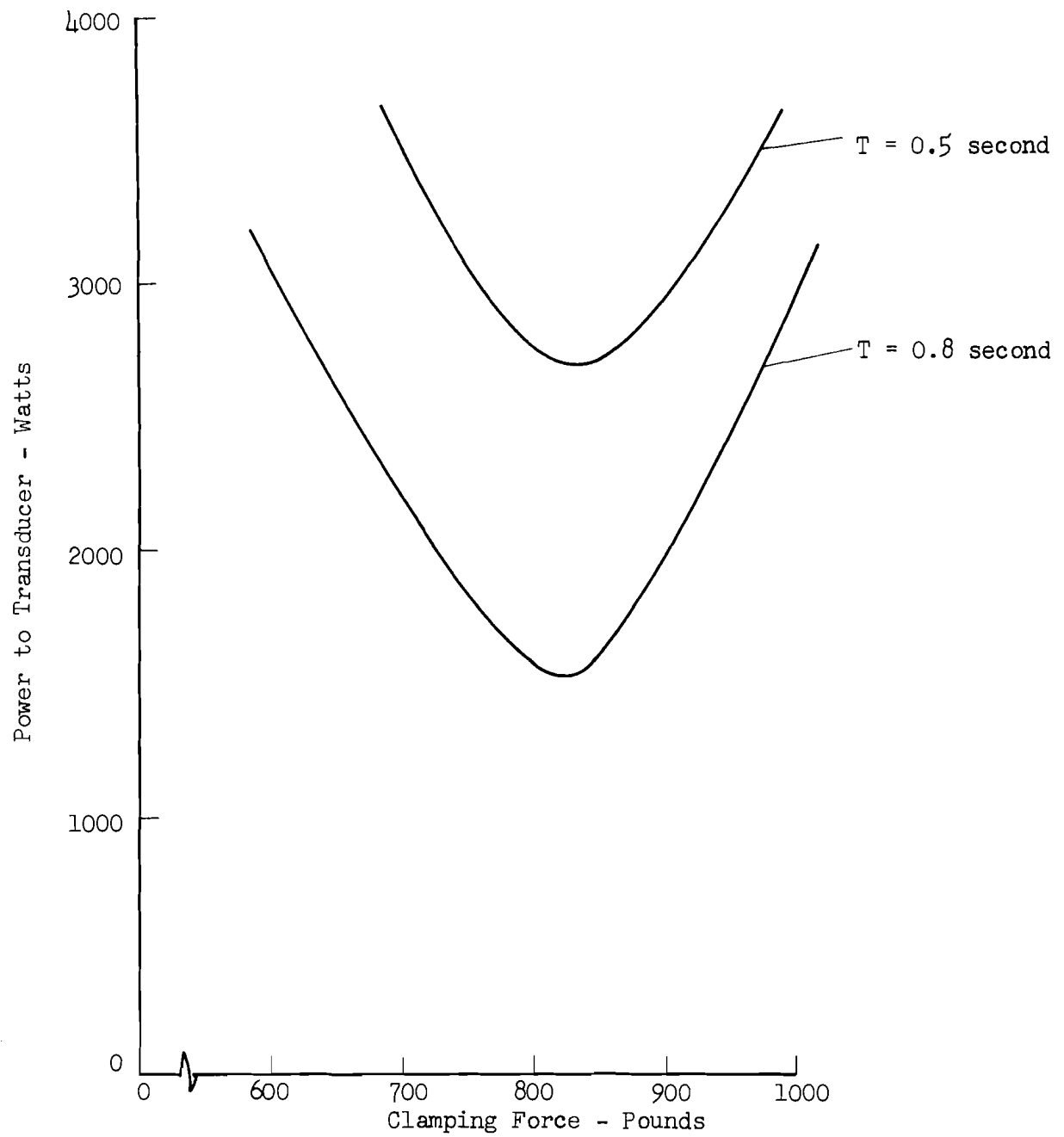(As in Figure 3)

Figure 9

THRESHOLD CURVES OF POWER AT TWO WELD INTERVALS
FOR 0.015-INCH B-66 NIOBIUM ALLOY

Pattern A

Pattern B

Pattern C

Pattern D
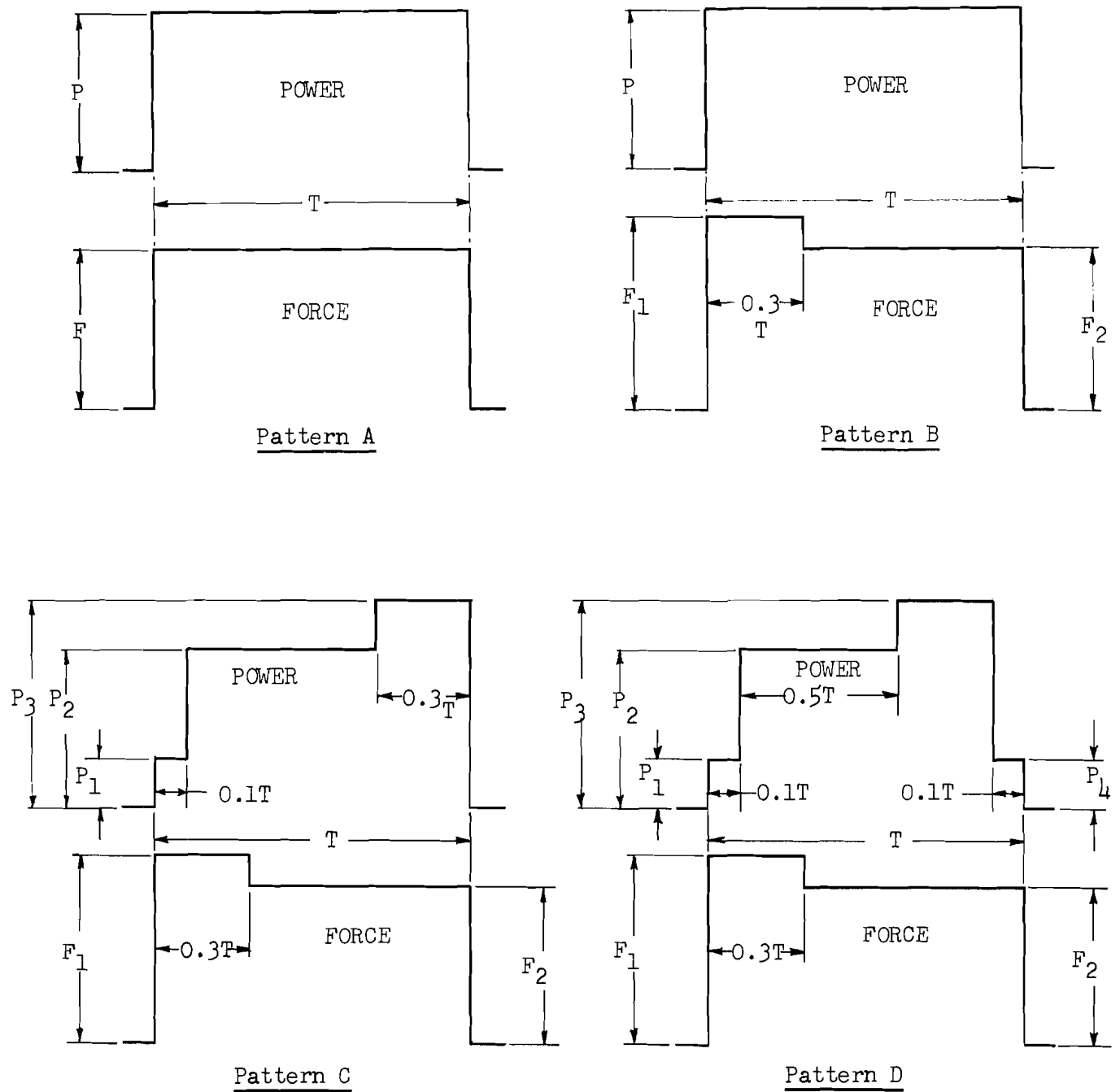
Figure 10

INITIAL POWER-FORCE PROGRAMS

P = Power
F = Clamping Force
T = Weld Time

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clamping force at the beginning, with power remaining constant; C provides increased force at the beginning and increased power at the end of the interval; D is essentially the same as C but with lower total weld energy. In the conduct of these experiments, these basic patterns were occasionally modified by brief reduction in power at the end of the weld cycle (at 0.9 T) in an effort to minimize tip sticking. The desired result was accomplished; it was demonstrated later, however, that with proper machine settings, tip sticking is not a problem.

Weld patterns E through K (Figure 11) were devised to observe the effects of more gradual introduction of power (and consequently of vibratory stresses and heat), with full power being applied only after half the weld interval had been completed. Several variations in clamping force were included in these patterns.

D.  MONITORING OF POWER-FORCE PROGRAMMING

During the early part of the work, power, force, and tip displacement were monitored during the formation of each weld, using the recording instrumentation described in Section III. Such data were obtained for all welds made in the non-refractory alloys and during part of the molybdenum alloy welding. The recorded traces showed that the established power and force program was being followed by the welding equipment, and further recording was limited to calibration performed at the beginning of each experiment day or when weldment materials were changed.

E.  TEMPERATURE MEASUREMENT

Earlier bond interface temperature measurements made during ultrasonic welding of iron, aluminum, and copper (3) under conditions of constant power and force had demonstrated that the initial rate of temperature rise was generally greatest and the maximum temperature achieved was lowest at the higher clamping forces; low clamping forces resulted in a lower rate of temperature rise with a higher maximum temperature. It has been further demonstrated (1) that the weld interface temperature obtained with any fixed power level is maximum at the clamping force which produces the best impedance match.

It was anticipated that temperature data obtained in conjunction with power-force programming would provide an indication of (a) impedance matching into the weldment and (b) the time at which the maximum temperature was achieved for initiation of bonding. Such measurements were made for various power-force programs used for the welding of 0.010-inch molybdenum-0.5% titanium alloy. These data were taken using a modified version of the single-wire thermocouple technique previously described (3,4), with temperature traces being recorded on a strip-chart recorder.

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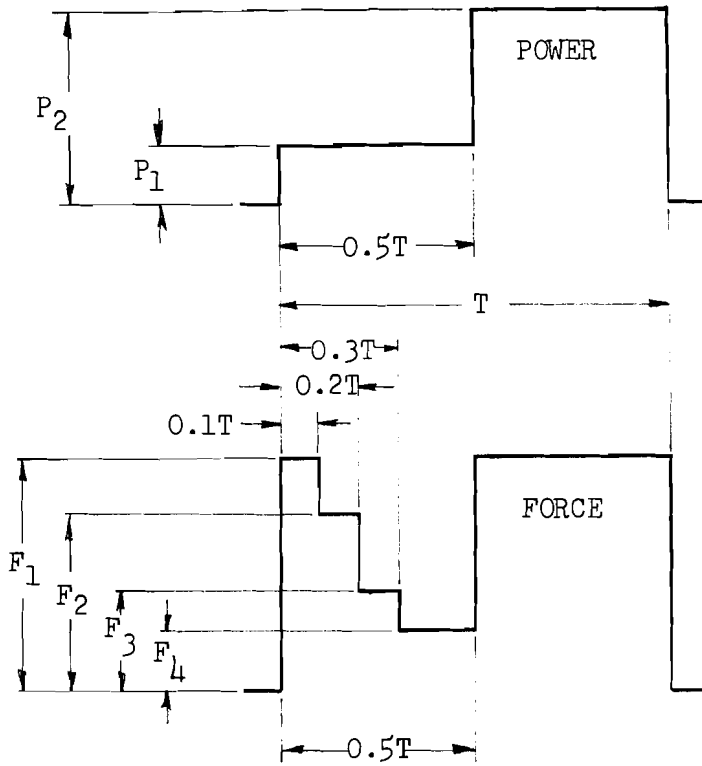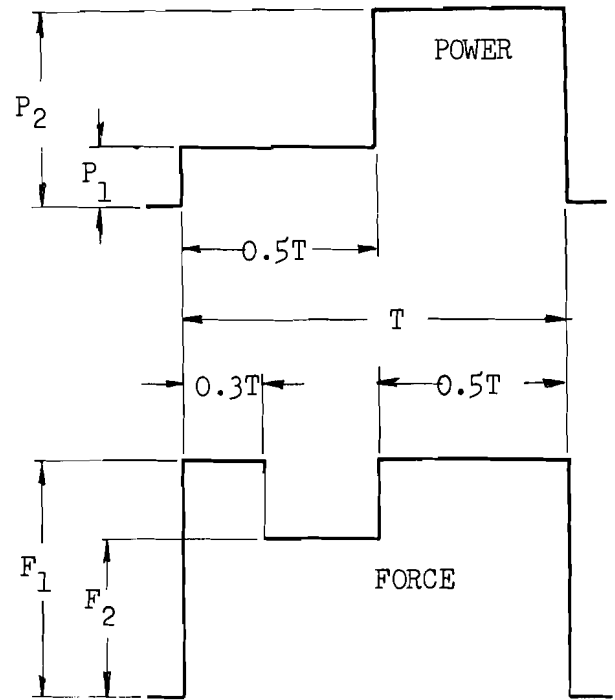
Pattern E

Pattern F
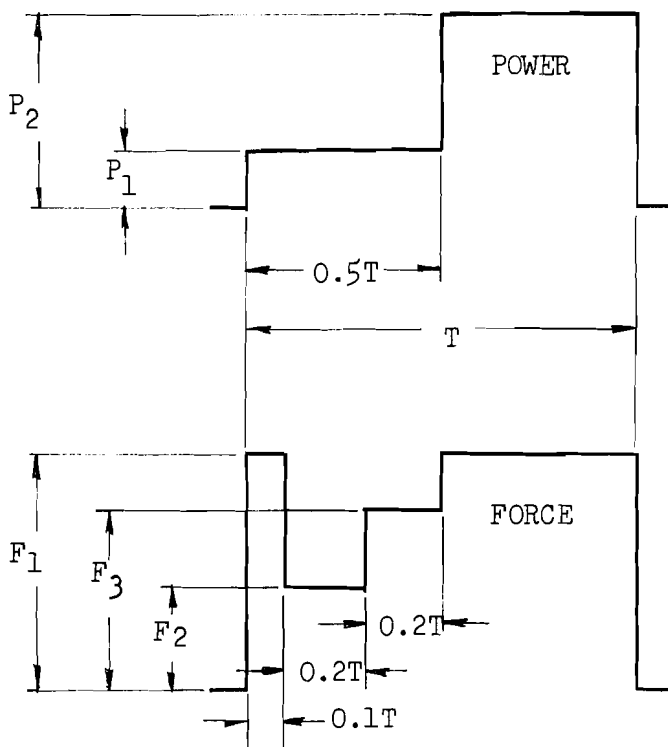
Pattern G
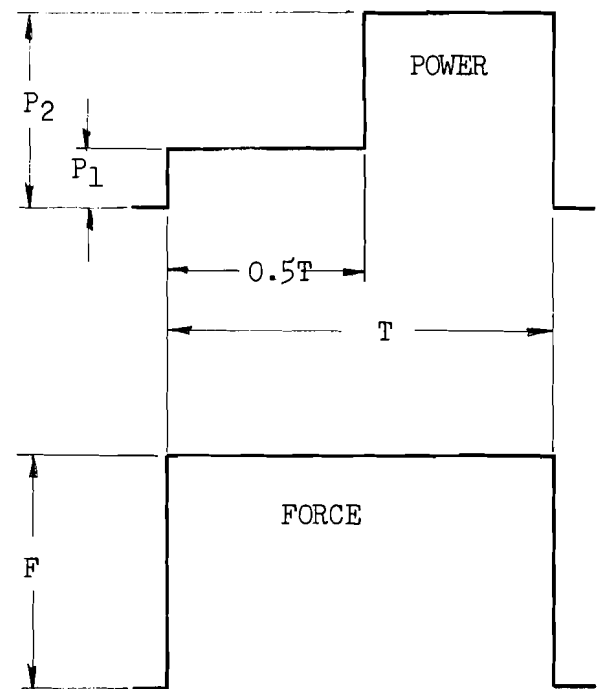
Pattern H

Figure 11

ADDITIONAL POWER-FORCE PROGRAMS
(P = Power, F = Clamping Force, T = Weld Time)

30
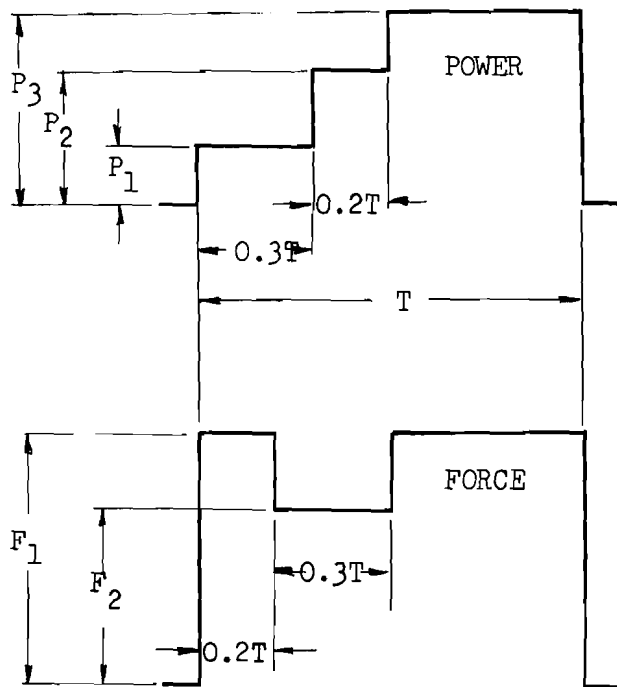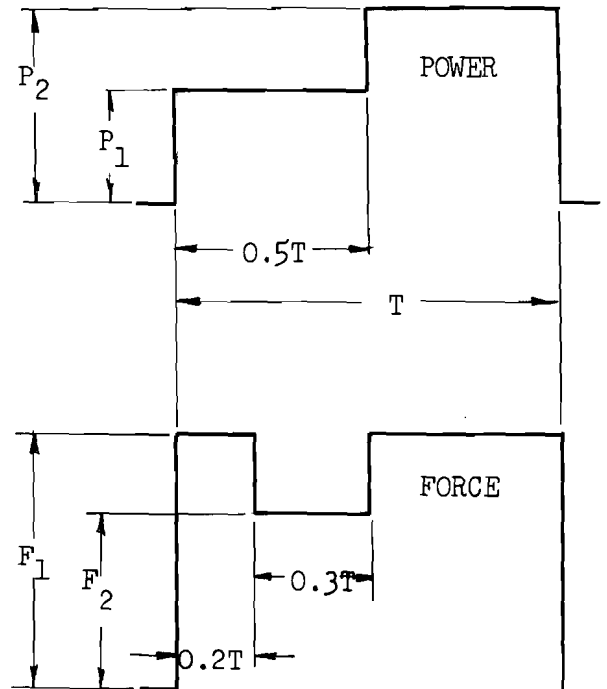
Pattern I

Pattern J
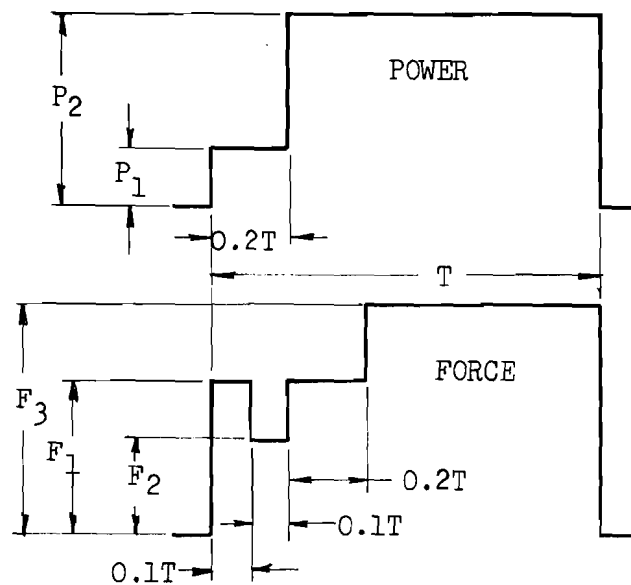


Pattern K

Figure 11 (Cont.)

ADDITIONAL POWER-FORCE PROGRAMS
(P = Power, F = Clamping Force, T = Weld Time)

F.   WELD EVALUATION

Weld quality was evaluated visually, by tensile-shear strength tests, and by metallographic examination of randomly selected specimens.

The tensile-shear tests were conducted using a Model TT-C-L Instron testing machine.  The strength values obtained for specimens made under the same conditions were analyzed statistically to determine the mean strength and the standard deviation of the group.

In addition, in order to provide a reliable comparison of weld strengths obtained with different power-force programs, probability analyses were made (11).  These analyses served to identify the weld strength differences obtained with the various patterns which were statistically significant on the 95 percent probability level.

Certain randomly selected weld specimens were sectioned parallel to and normal to the direction of tip vibration; these were mounted, etched, and examined metallographically to determine the incidence of cracks.  A few specimens were examined after planar sectioning (1), which involves successively removing material from the weldment in planes parallel to the weld interface.

## V. WELDING NON-REFRACTORY METALS
### WITH POWER-FORCE PROGRAMMING

Preliminary evaluation of power-force programming was carried out with several non-refractory metals, which have been relatively easy to weld ultrasonically. The objectives were first to evaluate the operation of the power-force programming system, and, second, to determine the effects of programmed welding on weld strength and strength variability and possibly on the metallurgical characteristics of the weld metal.

Two series of experiments were performed with a limited number of specimens. The first involved the welding of two gages of 2024-T3 aluminum alloy and one gage each of Type 304 stainless steel and Inconel X-750 with PFP patterns A, B, C, and D of Figure 10. When it appeared that significant effects on weld strength were obtained, more extensive investigation was carried out with the stainless steel and Inconel using selected PFP patterns.

Throughout the course of these studies, the sequence of PFP patterns was varied in a statistically random manner. This was accomplished by assigning a number to each of the PFP patterns, and then selecting PFP patterns for experimental use on the basis of the appearance of the assigned numbers in a random number table.

Values of power, force, and time for the various patterns were based on the standard welding machine settings for these materials as shown in Table VI. The only exception was Inconel X-750, for which the total weld time was inadvertently set at 1.5 seconds for the first series of experiments. This was corrected to 1.0 second for Series 2.

Strip-chart oscillograms of power, clamping force, and tip displacement were obtained for each of the welds made in both series. In all instances these traces verified the programmed power and force, as shown by the typical oscillograms for the stainless steel reproduced in Figures 12 and 13.

In addition to tensile-shear strength tests on the welded specimens, micrometer measurements were made of the weldment thickness in the weld zone and on unwelded areas of the specimens. Selected specimens were also examined metallographically.

The deformation measurements revealed no differences that could be directly attributed to power-force programs that were studied. Metallurgical studies disclosed possible differences for the various patterns, but these differences were not consistent among the four materials, and no conclusions could be drawn therefrom. There were marked differences, however, in the strengths obtained for the different patterns. These were analyzed statistically, and the details of the strength data and analysis are discussed below.

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Power Control
Signal To
Generator

Clamping Force

Sonotrode Tip
Displacement
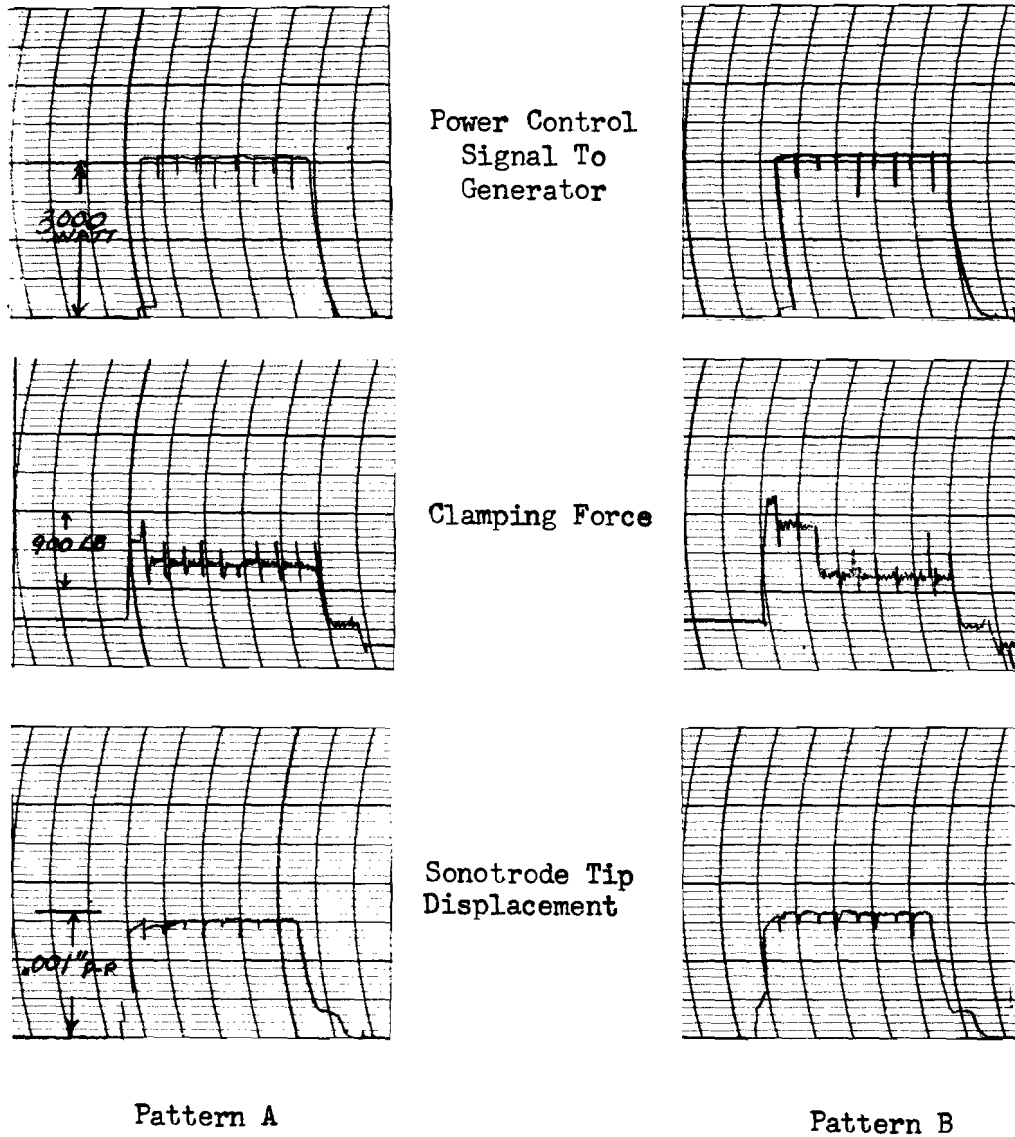
Pattern A                                      Pattern B

Figure 12

OSCILLOGRAMS FOR PROGRAMMED PATTERNS A AND B FOR POWER,
CLAMPING FORCE, AND SONOTRODE TIP DISPLACEMENT
WHILE WELDING 0.031-INCH THICK TYPE 304 STAINLESS STEEL
(Compare with Programmed Patterns in Table X)
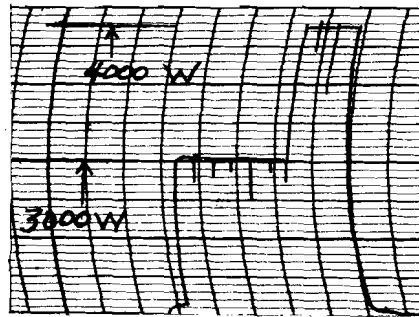
Power Control
Signal To
Generator
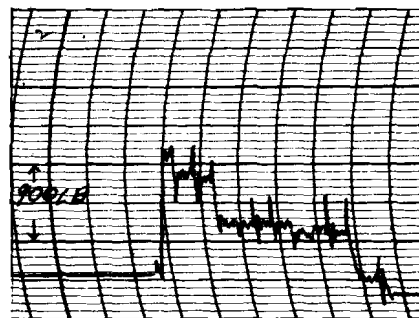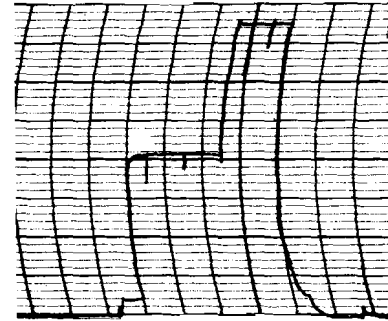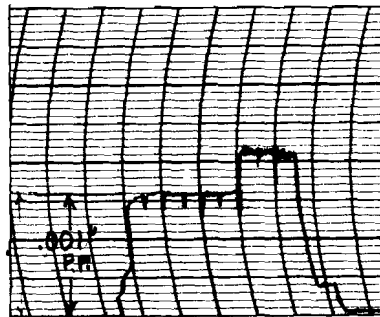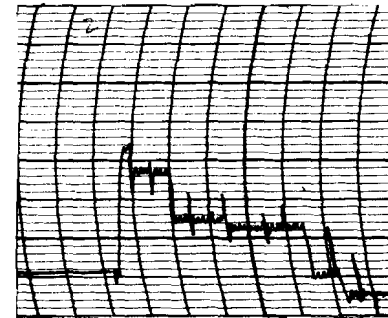
Clamping Force

Sonotrode Tip
Displacement
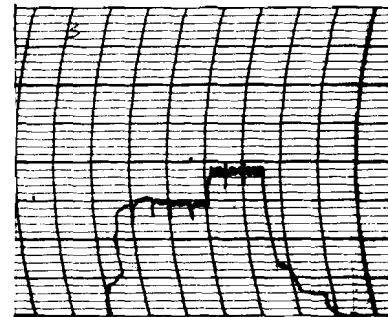
Pattern C                    Pattern D

Figure 13

OSCILLOGRAMS FOR PROGRAMMED PATTERNS C AND D FOR POWER,
CLAMPING FORCE, AND SONOTRODE TIP DISPLACEMENT
WHILE WELDING 0.031-INCH THICK TYPE 304 STAINLESS STEEL
(Compare with Programmed Patterns in Table X)

## A.  2024-T3 BARE ALUMINUM ALLOY

The programs, including the power and force values used in each case, for 0.050-inch and 0.063-inch aluminum alloy are shown in Tables VII and VIII. Also included are the individual shear strengths, the mean strength, and the standard deviation pertinent to each pattern. It is noted that only three specimens were tested for each pattern, and the statistical reliability of the data may be marginal. These data did, however, indicate certain trends.

For the 0.050-inch material (Table VII), the average weld strength for Patterns C and D was approximately twice that obtained with A and B. Statistical analysis of the probability that these differences are significant is presented in Table IX. On the basis of the limited number of samples, the analysis shows a significant difference between Patterns A and C, between A and D, between B and C, and between B and D. The differences between A and B are not significant, nor are those between C and D.

It is noted that A represents non-programmed welding, and B involves only programmed clamping force. Apparently this single adjustment, within the range used, did not affect weld quality in this material. C and D involve programming of both power and force, and the improvement is evident. The results obtained with D are superior even though the total energy applied during welding was slightly less than in the case of Pattern C.

For the 0.063-inch material (Table VIII), the welding machine had insufficient power to provide a power increase for the last three-tenths of the weld time, as required for Patterns C and D. Consequently, Pattern C was omitted from this experiment, and Pattern D was merely a modification of B to provide for reduced power at the end of the weld cycle. Consequently, the data for D are not necessarily representative of that which would be obtained with the power increase (as shown in D for the 0.050-inch material). Statistical analysis of the strength values (Table IX) shows a significant difference between A and B and between A and D. Apparently with this thicker material the programmed clamping force (without programmed power) did promote higher strength welds. This is true even for Pattern D, in which the total weld energy was less than for Pattern A.

## B.  TYPE 304 STAINLESS STEEL

The program patterns and results for the 0.031-inch stainless steel are presented in Tables X and XI, and the statistical analysis for probability is delineated in Table XII.

In the first series of tests, which involved only three or four specimens for each pattern, the results duplicated those obtained with the 0.050-inch aluminum alloy: a statistically significant difference exists between A and C,

Table VII

EXPERIMENTAL WELDING OF 0.050-INCH 2024-T3 BARE ALUMINUM ALLOY
WITH POWER-FORCE PROGRAMMING
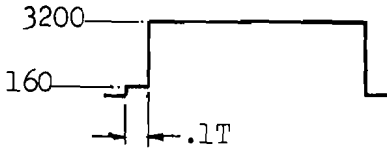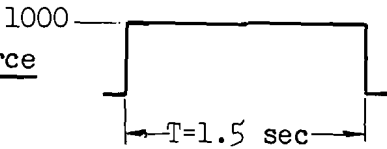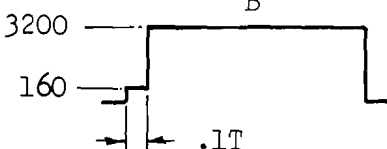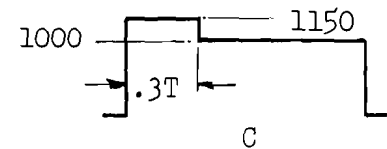
| | | PFP Pattern | Total Weld Time, sec | Total Weld Energy, watt-sec | Individual Shear Strengths, pounds | Average Shear Strength, pounds | Standard Deviation, pounds |
|---|---|---|---|---|---|---|---|
| Power | A | A | 1.5 | 4340 | 555 965 300 | 616 | 328 |
| Force | | B | 1.5 | 4340 | 540 400 595 | 517 | 101 |
| | C | C | 1.5 | 4790 | 1545 825 1265 | 1217 | 363 |
| | D | D | 1.5 | 4340 | 1255 1360 1390 | 1335 | 71 |

Table VIII

EXPERIMENTAL WELDING OF 0.063-INCH 2024-T3 BARE ALUMINUM ALLOY
WITH POWER-FORCE PROGRAMMING

(Welded With Foil Interleaf of 0.001-Inch 1100-H18 Aluminum)
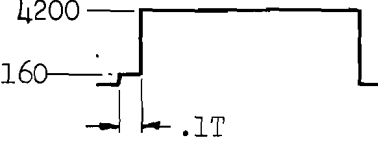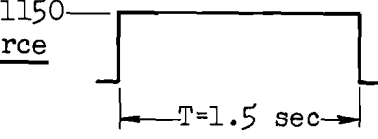
| | PFP Pattern | Total Weld Time, sec | Total Weld Energy, watt-sec | Individual Shear Strengths, pounds | Average Shear Strength, pounds | Standard Deviation, pounds |
|---|---|---|---|---|---|---|
| A | A | 1.5 | 5690 | 1060<br>900<br>790 | 917 | 136 |
| B | B | 1.5 | 5690 | 1025<br>1340<br>1010 | 1125 | 186 |
| D | D | 1.5 | 5090 | 1230<br>1080<br>1030 | 1113 | 104 |

**A**

Power
4200
160
.1T

1150
Force
T=1.5 sec

**B**

4200
160
.1T
1150 —1200
.3T

**D**

4200
160
.1T        .1T
1150 —1200
.3T

38

Table IX

STATISTICAL ANALYSIS TO ESTABLISH
WHETHER A SIGNIFICANT DIFFERENCE IN WELD STRENGTH IS OBTAINED
WITH VARIOUS POWER-FORCE PROGRAMS
FOR 2024-T3 ALUMINUM ALLOY

| Material | Gage, inch | PFP Pattern | Tensile-Shear Strength, pounds | | No. of Samples | Probability That Variation Is Caused by Chance[*] Comparison With Pattern | | |
|---|---|---|---|---|---|---|---|---|
| | | | Mean, $\mu$ | Standard Deviation, $\sigma$ | | A | B | C |
| 2024-T3 Bare Aluminum | 0.050 | A | 616 | 328 | 3 | | | |
| | | B | 517 | 101 | 3 | >0.20 | | |
| | | C | 1217 | 363 | 3 | <0.01 | <0.01 | |
| | | D | 1335 | 71 | 3 | <0.01 | <0.01 | >0.20 |
| 2024-T3 Bare Aluminum With Foil Interleaf | 0.063 | A | 917 | 136 | 3 | | | |
| | | B | 1125 | 186 | 3 | <0.01 | | |
| | | D | 1113 | 104 | 3 | <0.01 | >0.40 | |

[*] A probability of less than 0.05 indicates a 95% probability that the difference is not due to random variation and is usually considered adequate evidence of significance.

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Table X

EXPERIMENTAL WELDING OF 0.031-INCH TYPE 304 STAINLESS STEEL
WITH POWER-FORCE PROGRAMMING

(Series 1)

| | PFP Pattern | Total Weld Time, sec | Total Weld Energy, watt-sec | Individual Shear Strengths, pounds | Average Shear Strength, pounds | Standard Deviation, pounds |
|---|---|---|---|---|---|---|
| A | A | 1.0 | 2810 | 780 865 780 | 808 | 49 |
| B | B | 1.0 | 2810 | 860 790 850 630 | 783 | 118 |
| C | C | 1.0 | 3105 | 860 920 875 895 | 883 | 32 |
| D | D | 1.0 | 2810 | 915 920 825 990 | 913 | 83 |

Table XI

EXPERIMENTAL WELDING OF 0.031-INCH TYPE 304 STAINLESS STEEL
WITH POWER-FORCE PROGRAMMING
(Series 2)

| | PFP Pattern | Total Weld Time, sec | Total Weld Energy, watt-sec | Individual Shear Strengths, pounds | Average Shear Strength, pounds | Standard Deviation, pounds |
|---|---|---|---|---|---|---|
| **A** <br> Power: 3200, 80, .1T <br> Force: 690, T=1.0 sec | A | 1.0 | 2890 | 800 <br> 1020 <br> 1040 <br> 1030 <br> 1080 <br> 940 <br> 1000 <br> 990 <br> 1080 <br> 1070 | 1005 | 84 |
| **C** <br> Power: 4100, 3200, 80, .3T, .1T <br> Force: 900, 690, .3T | C | 1.0 | 3160 | 1130 <br> 1120 <br> 1190 <br> 970 <br> 1010 <br> 940 <br> 940 <br> 1240 <br> 1050 <br> 1040 | 1063 | 104 |
| **D** <br> Power: 4100, 3200, 80, .3T, .1T, .1T <br> Force: 900, 690, .3T | D | 1.0 | 2850 | 1120 <br> 1050 <br> 780 <br> 1090 <br> 860 <br> 980 <br> 900 <br> 960 <br> 1040 <br> 1080 | 986 | 111 |

Table XII

STATISTICAL ANALYSIS TO ESTABLISH
WHETHER A SIGNIFICANT DIFFERENCE IN WELD STRENGTH IS OBTAINED
WITH VARIOUS POWER-FORCE PROGRAMS
FOR 0.031-INCH TYPE 304 STAINLESS STEEL

| | PFP Pattern | Tensile-Shear Strength, pounds | | No. of Samples | Probability That Variation Is Caused by Chance* | | |
| | | Mean, $\mu$ | Standard Deviation, $\sigma$ | | Comparison With Pattern | | |
| | | | | | A | B | C |
|---|---|---|---|---|---|---|---|
| Series 1 | A | 808 | 49 | 3 | | | |
| | B | 783 | 118 | 4 | > 0.10 | | |
| | C | 883 | 32 | 4 | < 0.01 | < 0.05 | |
| | D | 913 | 83 | 4 | < 0.01 | < 0.02 | > 0.05 |
| Series 2 | A | 1005 | 84 | 10 | | | |
| | C | 1063 | 104 | 10 | > 0.6 | | |
| | D | 986 | 111 | 10 | > 0.6 | | > 0.1 |
| Series 1 and 2 Combined | A | 960 | 115 | 13 | | | |
| | C | 983 | 165 | 14 | > 0.6 | | |
| | D | 965 | 104 | 14 | > 0.9 | | > 0.7 |

*A probability of less than 0.05 indicates a 95% probability that the difference is not due to random variation and is usually considered adequate evidence of significance.

between A and D, between B and C, and between B and D, but not between A and B and not between C and D. Again it appeared that improved quality welds could be obtained by programming both power and force in the patterns noted.

The second series involved a greater number of specimens (ten) for each pattern. Since Pattern B had provided essentially the same results as A in Series 1, B was omitted from this second group of tests. The results did not confirm those obtained in the first series. Although weld strengths were somewhat higher for the second series, there was no statistically significant difference in comparing any two patterns.

Since the welds for each pattern were made under the same conditions for both series, the results for Patterns A, C, and D were combined and re-analyzed statistically. The differences in this case were found to be not significant, and it appeared that the selected power-force programs had no beneficial effect in welding this material. Since this material was not of primary interest to the program, no further effort was devoted to it.

C. INCONEL X-750

The programs and results for the 0.016-inch Inconel X-750 are presented in Tables XIII, XIV, and XV.

This material, which was likewise welded in two series of experiments, showed the same statistical results for both series, and these generally duplicated those obtained for the 0.050-inch aluminum alloy. As before, the selected clamping force program alone had no significant effect, but the selected power and force programs as in C and D effected improved quality welds.

Thus this preliminary work indicated improved welding with PFP Patterns C and D and provided a preliminary and very limited basis on which to proceed with welding of the refractory metals.

Table XIII

EXPERIMENTAL WELDING OF 0.016-INCH INCONEL X-750
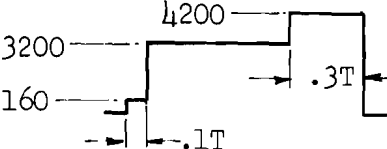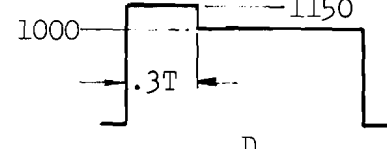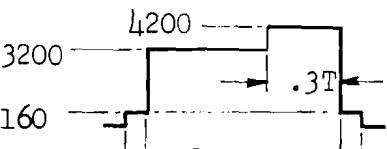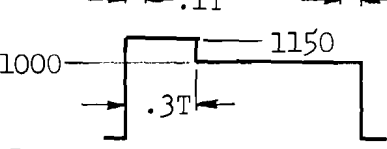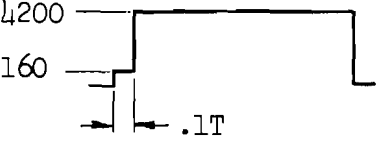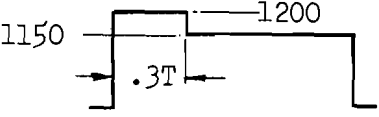WITH POWER-FORCE PROGRAMMING

(Series 1)

| | PFP Pattern | Total Weld Time, sec | Total Weld Energy, watt-sec | Individual Shear Strengths, pounds | Average Shear Strength, pounds | Standard Deviation, pounds |
|---|---|---|---|---|---|---|
| A | A | 1.5 | 2460 | 480 500 460 490 | 483 | 21 |
| B | B | 1.5 | 2460 | 520 480 490 450 | 485 | 35 |
| C | C | 1.5 | 2690 | 560 495 500 520 | 519 | 36 |
| D | D | 1.5 | 2450 | 560 510 560 495 | 531 | 25 |



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## Table XIV

### EXPERIMENTAL WELDING OF 0.016-INCH INCONEL X-750
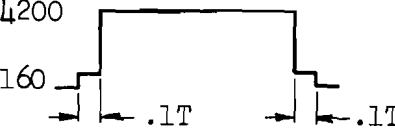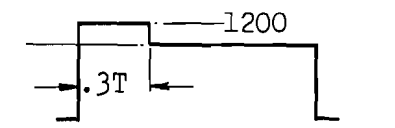### WITH POWER-FORCE PROGRAMMING
### (Series 2)

| | PFP Pattern | Total Weld Time, sec | Total Weld Energy, watt-sec | Individual Shear Strengths, pounds | Average Shear Strength, pounds | Standard Deviation, pounds |
|---|---|---|---|---|---|---|
| Pattern A | A | 1.0 | 1640 | 235 430 350 180 355 330 395 | 325 | 88 |
| Pattern C | C | 1.0 | 1810 | 435 500 505 410 500 450 395 515 460 | 463 | 44 |
| Pattern D | D | 1.0 | 1660 | 445 475 465 415 465 495 415 480 | 457 | 29 |

Pattern A diagram labels:
Power: 1800, 240, .1T
Force: 275, T=1.0 sec

Pattern C diagram labels:
Power: 2300, 1800, 240, .3T, .1T
Force: 275, 380, .3T

Pattern D diagram labels:
Power: 2300, 1800, 240, .3T, .1T, .1T
Force: 275, 380, .3T

Table XV

STATISTICAL ANALYSIS TO ESTABLISH
WHETHER A SIGNIFICANT DIFFERENCE IN WELD STRENGTH IS OBTAINED
WITH VARIOUS POWER-FORCE PROGRAMS
FOR 0.016-INCH INCONEL X-750

| | PFP Pattern | Tensile-Shear Strength, pounds | | No. of Samples | Probability That Variation Is Caused by Chance[*] | | |
| | | Mean, $\mu$ | Standard Deviation, $\sigma$ | | Comparison With Pattern | | |
| | | | | | A | B | C |
| Series 1 | A | 483 | 21 | 4 | | | |
| | B | 485 | 35 | 4 | > 0.40 | | |
| | C | 519 | 36 | 4 | < 0.01 | < 0.03 | |
| | D | 531 | 25 | 4 | < 0.01 | < 0.01 | > 0.20 |
| Series 2 | A | 325 | 88 | 7 | | | |
| | C | 463 | 44 | 9 | < 0.01 | | |
| | D | 457 | 29 | 8 | < 0.01 | | > 0.70 |

[*]A probability of less than 0.05 indicates a 95% probability that the difference is not due to random variation and is usually considered adequate evidence of significance.

VI.  PRELIMINARY MEASUREMENTS

OF TIP DISPLACEMENT AND INTERFACE TEMPERATURE

A.  TIP DISPLACEMENT STUDIES

Tip displacement is related to the vibratory power being delivered to the workpiece, and thus is affected by the clamping force applied through the tip and by the electrical power being delivered to the transducers that provide the vibratory power to the tip.  If the tip is not "coupled" to the work, it can slip; if it is coupled to the work, higher displacements indicate large strain at and adjacent to the tip in the surface of the workpieces. Thus, tip displacement data provide a measure of the time required for the tip to "couple" into the workpieces, as well as an indication of the response of the ultrasonic system to changes in welding conditions, such as produced by power-force programming.  Obviously such data alone do not permit determination of vibratory power delivery, weld zone impedance, etc., because knowledge of the forces against which the tip displacements operate is also required for power determinations, and these were not provided.

Initial experiments were conducted to determine the level of increase in clamping force required to induce early coupling of the sonotrode tip to the weld metal.  These were conducted with a soft material, 0.040-inch 2024-T3 aluminum alloy, and appeared to be confirmed with 0.010-inch molybdenum-0.5% titanium alloy.  Figure 14 shows a series of sonotrode tip displacement traces for the aluminum alloy, obtained at a constant power and with programmed force.  From these data it appears that all of the force levels examined were adequate to produce coupling into this gage of 2024-T3 aluminum alloy, since neither the initial nor the later displacements of the weld interval were extreme.  In the third program of Figure 14, it will be noted that application of the 800-pound clamping force produced a reduction in displacement, and in the fourth program the 1000-pound clamping force also caused a reduction in amplitude toward the end of the weld interval.

Tip displacement oscillograms were recorded during welding of 0.010-inch molybdenum-0.5% titanium alloy for each of the program patterns of Figures 10 and 11.  In all cases, selected power and force values were based on the standard welding machine settings selected for this alloy and gage (700 pounds clamping force, 3000-3200 watts power, and 0.3-0.5 second weld time). The programmed values used and tip displacement traces are presented in Figure 15.  Pattern D is not included since it essentially duplicates the program in C; likewise K is not included since it is identical to F for the power delivery portion of the weld interval (K includes a post-weld forge interval at high clamping force after the ultrasonic power is cut off).

Clamping Force – Pounds                    Tip Displacement (Mils)
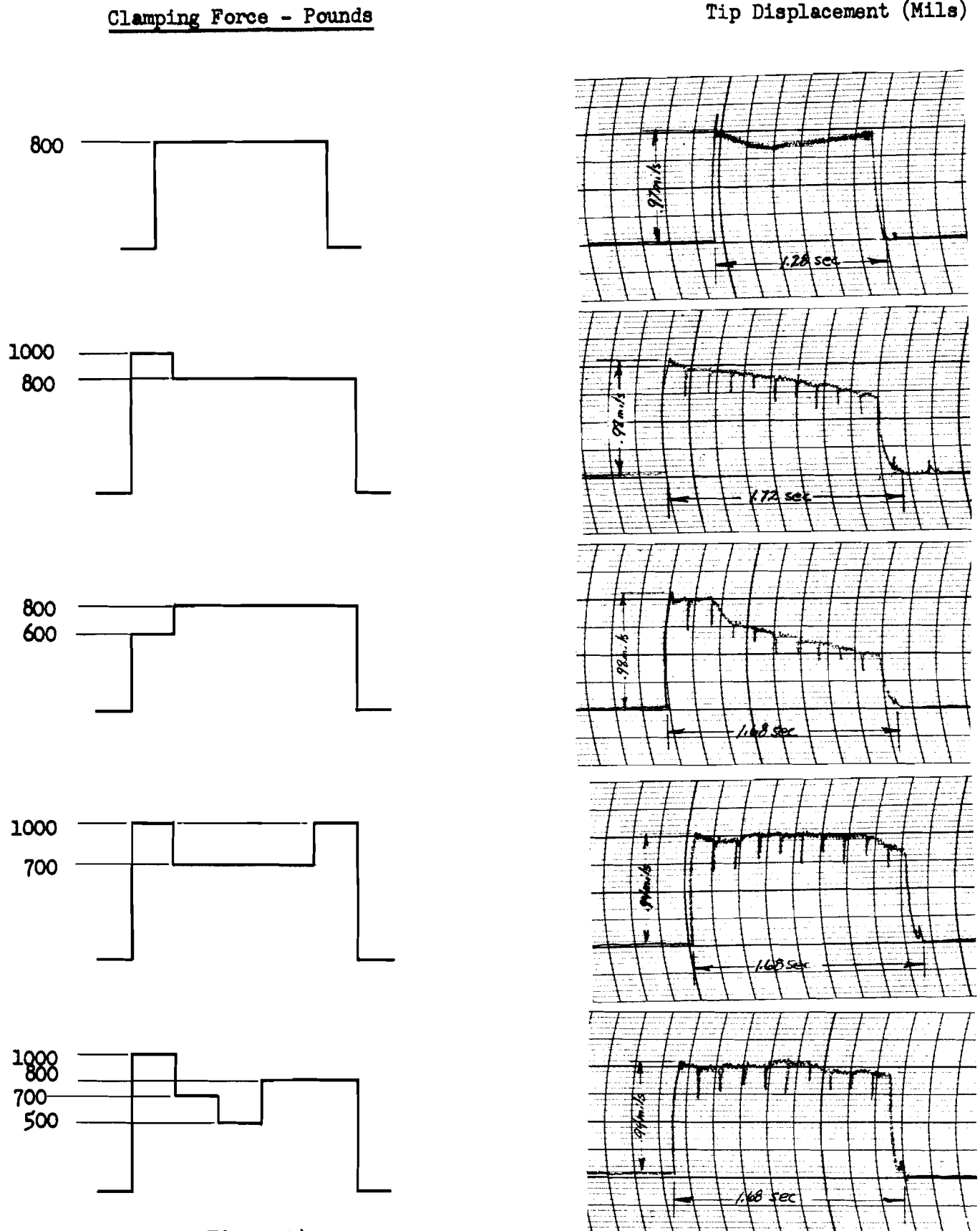


Figure 14

TIP DISPLACEMENT TRACES FOR VARIOUS PATTERNS
OF PROGRAMMED FORCE AT CONSTANT POWER

Material:  0.040-inch 2024T3 Aluminum Alloy

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## PATTERNS

Force      Power

700     3000

- A -

T=0.5 sec    T = 0.5 sec

850   700    3000

- B -

.3T

850   700    3150   3600

- C -

.3T       .3T

525   400   300   750    1100   3200

- E -

525   750    1100   3200

- F -
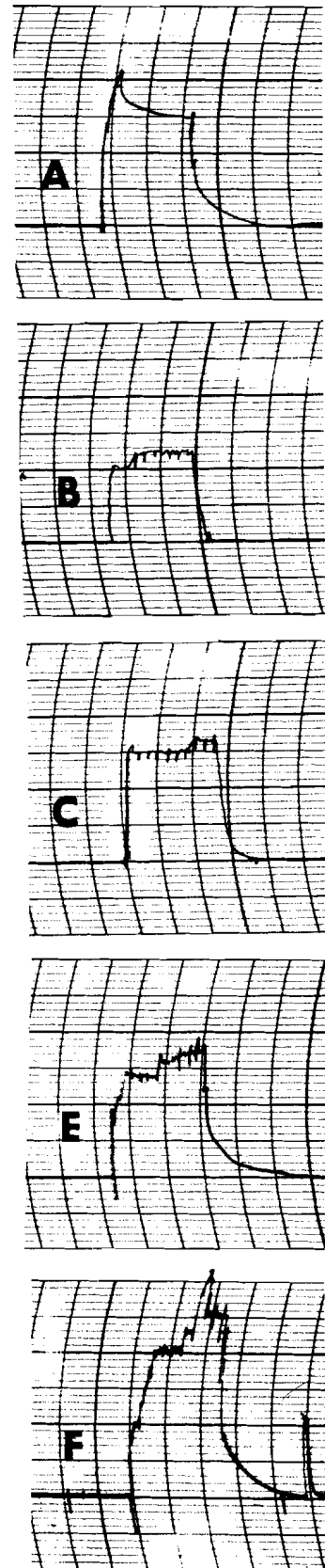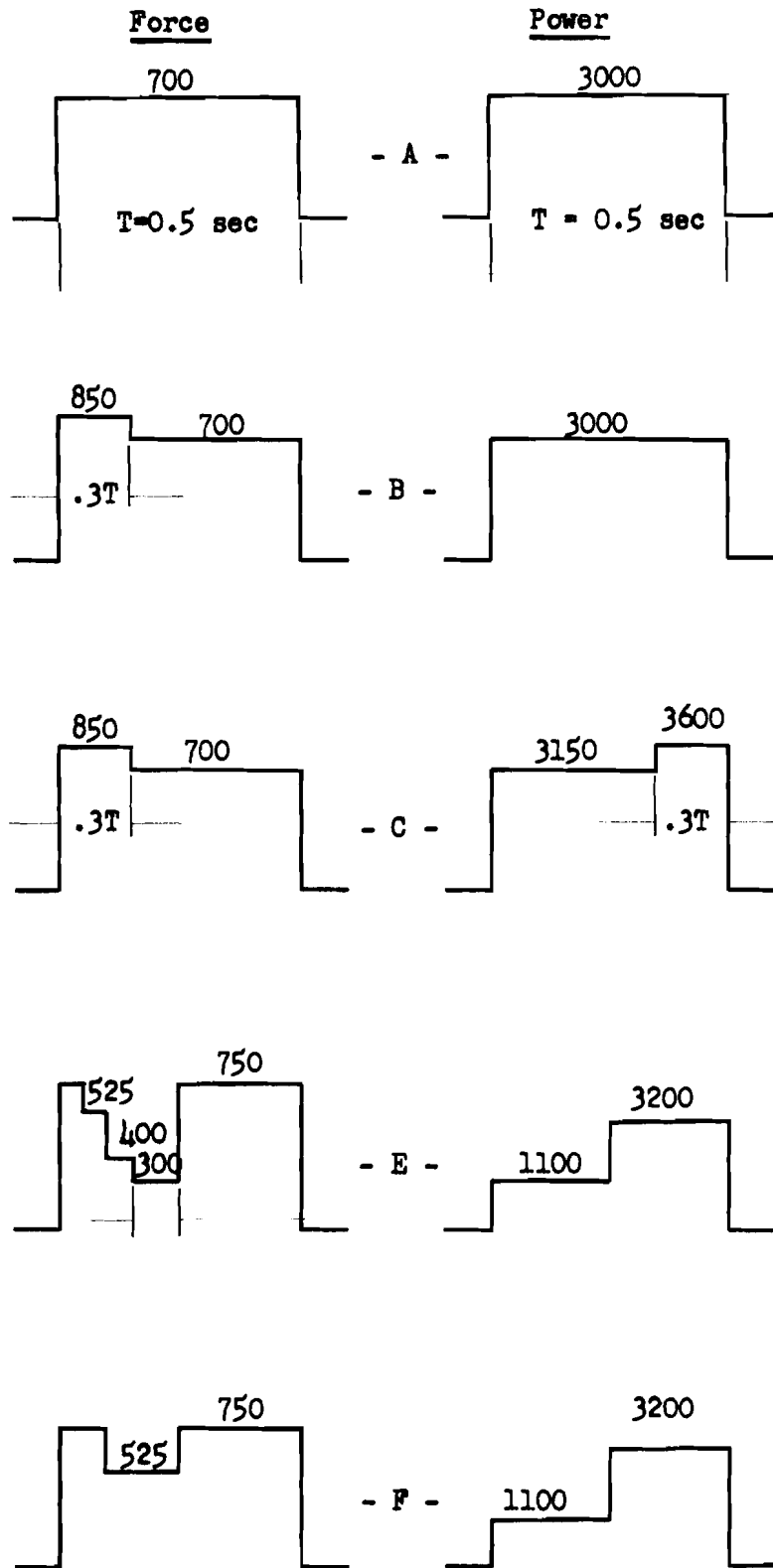


**Figure 15**

OSCILLOGRAM TRACINGS OF TIP DISPLACEMENT FOR
VARIOUS PFP PATTERNS WHILE WELDING
0.010-INCH MOLYBDENUM-0.5% TITANIUM ALLOY
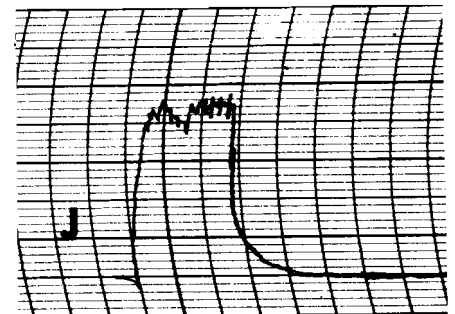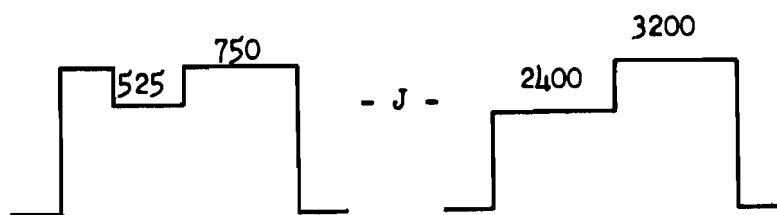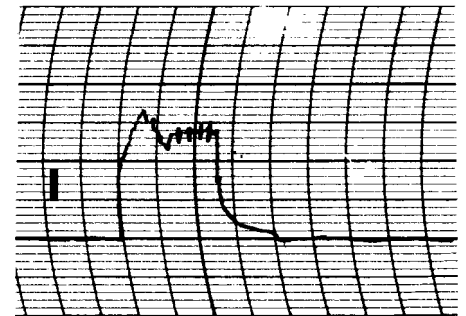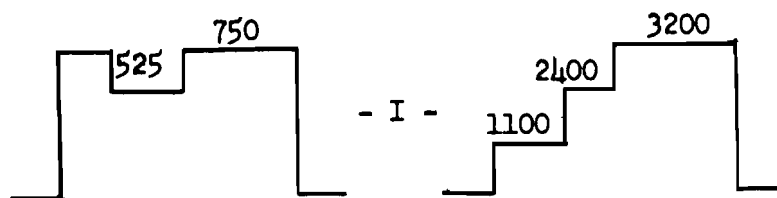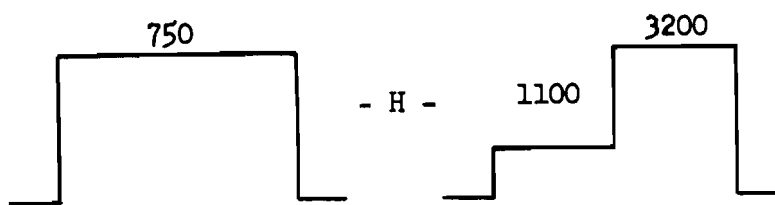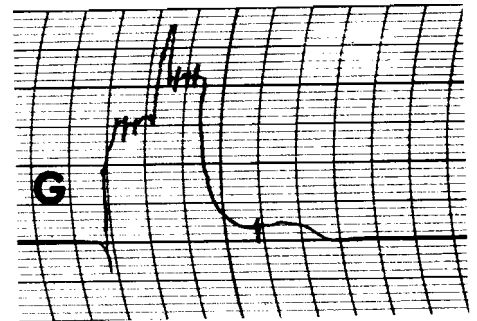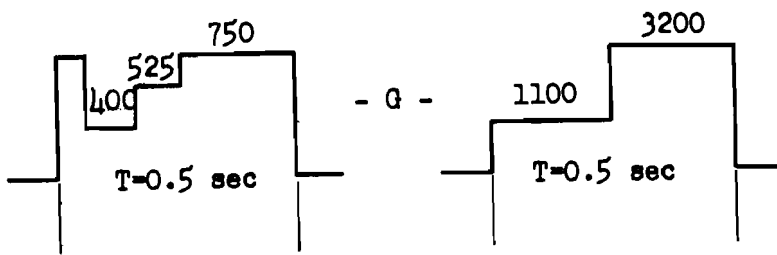
Figure 15 (Concluded)

The oscillogram for Pattern A shows excessive tip displacement on initiation of the weld cycle, resulting from tip slippage and inadequate coupling to the weldment. In patterns E, F, G, H, and I, the low power at the beginning of the weld cycle was not sufficient to drive the tip to a large amplitude, and coupling to the weldment occurred slowly. When the higher power was applied, and tip displacement increased to a larger amplitude, as shown particularly in F and G, indicating that coupling did not occur at the low pressure. Pattern C provided the most constant tip displacement throughout the weld cycle; however, the precise effects of constant displacement are not known.

These tip displacement data were supplemented by tensile-shear strength tests on welds made with the various patterns. In some instances welding was unsatisfactory; in others, erratic strengths were obtained; such patterns were not further used.

Patterns A, B, C, and D were selected for further welding.

B.   INTERFACE TEMPERATURE STUDIES

The influence of temperature on yield strength of the body-centered cubic metals is particularly evident by observation of the ductile:brittle behavior of these materials. The ductile:brittle transition occurs in the temperature region where the yield strength increases rapidly as the temperature is lowered. Brittle fracture occurs when the yield strength exceeds the fracture strength. The transition temperature is that temperature below which the metal fractures with little or no plastic deformation.

The refractory metals niobium, vanadium, molybdenum, tungsten, and chromium display ductile:brittle transition behavior. The actual transition temperature for these materials is significantly influenced by strain rate, interstitial content, metallurgical history, state of stress, etc. The beginning of ductile behavior in tension of these materials varies from -300°C for commercially pure niobium to +250°C for annealed tungsten (see Figure 16).

Welding processes that involve melting and consequently drastic thermal cycling must be modified to inhibit cracking resulting from high stresses imposed by steep temperature gradients. Several methods of approach are currently being investigated, related to both the metallurgical properties of the metals and alloys and the welding techniques. The development of alloys with low transition temperature and increased ductility and pre-heating and/or post-heating during welding are principal examples of these approaches.

Although average temperatures achieved during ultrasonic welding do not exceed 35 to 50 percent of the absolute melting point of the materials being joined (4), temperature gradients do exist, which, superimposed on the alternating vibratory stresses, may produce total stresses sufficient to produce cracks during welding. Cracking of molybdenum and tungsten during ultrasonic welding has been reported (1).
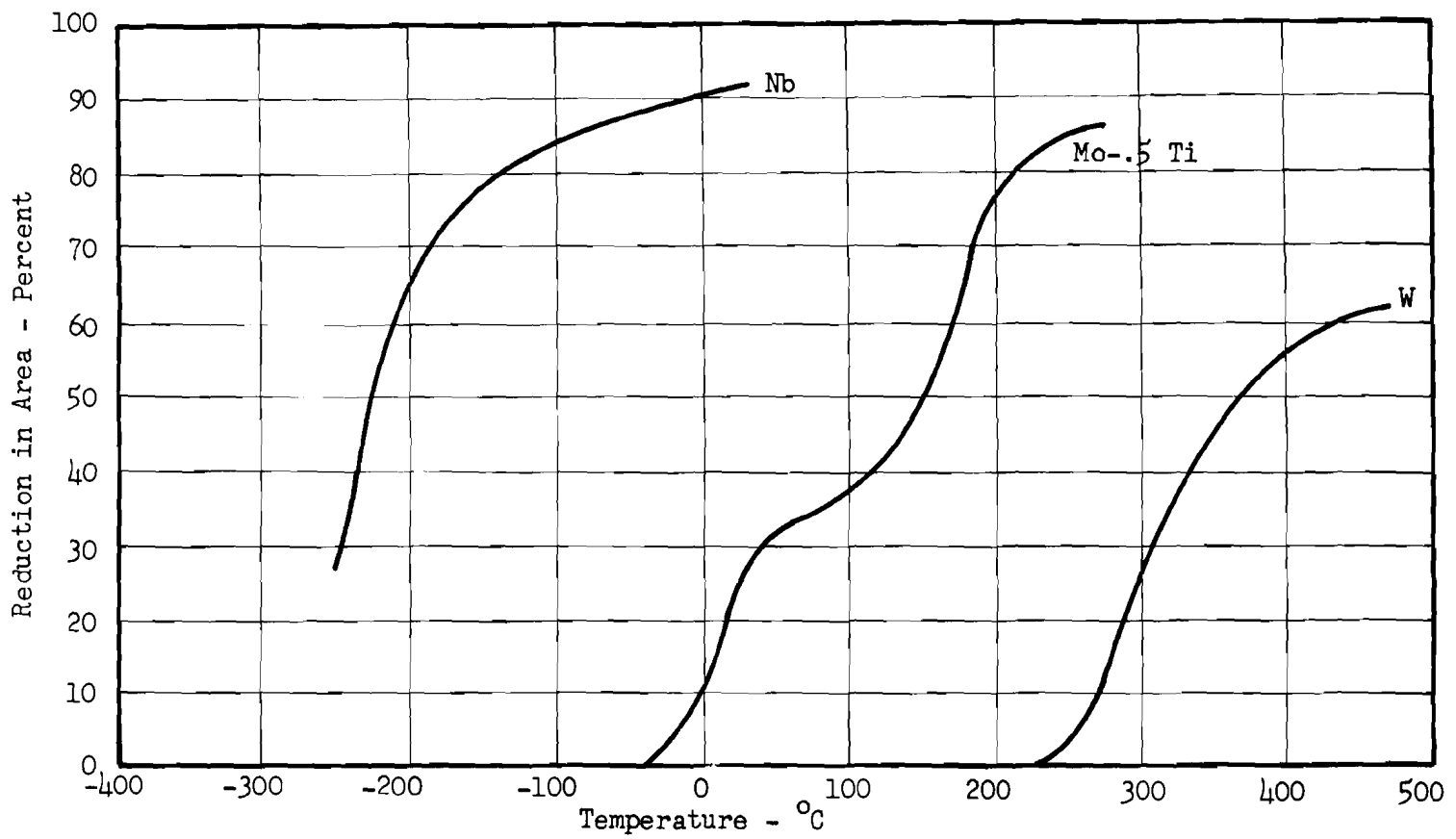
Figure 16

DUCTILE:BRITTLE TRANSITION CHARACTERISTICS
OF REFRACTORY METALS (TENSION DATA)
(Ref. 12)

The use of pre-heating and controlled cooling methods during welding of refractory metals and alloys can be applied to ultrasonic welding. Inasmuch as little is known about the effect of rapidly alternating stresses such as are associated with ultrasonic vibration, and particularly when those stresses are superimposed on changing temperature, it is clear that considerable work will be needed to establish a correlation between PFP welding and the properties of the material being welded, and thus to become acquainted with and properly apply power-force programming to the ultrasonic welding process. The work here reported essentially shows that PFP is effective and that, with proper understanding and use, it should fulfill the purposes for which it was intended.

It was anticipated that power-force programming would permit some degree of control over the rate of heating and cooling of the weld metal, and, within limits, the average temperatures achieved during various portions of the weld cycle. Materials displaying high transition temperatures, for example, may require a pre-weld heating period to raise the temperature well above the transition temperature. Other situations may occur in which weld strength degradation from over-aging, solution annealing, etc., might be prevented by controlling the temperature and build-up of alternating stresses via a suitable power-force program.

Programmed patterns E through K were devised to observe the extent of this control. Using the single-wire thermocouple insert technique (3), interface temperature traces were obtained for each of these patterns applied during welding of 0.010-inch molybdenum-0.5% titanium alloy. The traces are reproduced in Figure 17.

The recorded peak temperatures ranged from $720^\circ$ to $900^\circ C$ and are consistent with earlier data (4) showing an average peak temperature of $777^\circ C$ for this alloy. The temperatures of $720^\circ$ to $900^\circ C$ represent 35 to 40 percent of the absolute melting point ($2883^\circ K$), which also agrees with the earlier observations (4).

The temperature traces of Figure 17 generally follow the programmed power pattern. They seem to be characterized by a rapid rate of temperature rise with initial application of power and leveling off to a plateau, then a further temperature increase to a maximum as maximum power is applied. Some variations are apparent in these traces as a consequence of the varied clamping force patterns. However, the differences are not sufficient to allow firm conclusions relating to the different patterns. Available time and funds did not permit furtherance of this work to obtain sufficient data for rigorous statistical analysis.
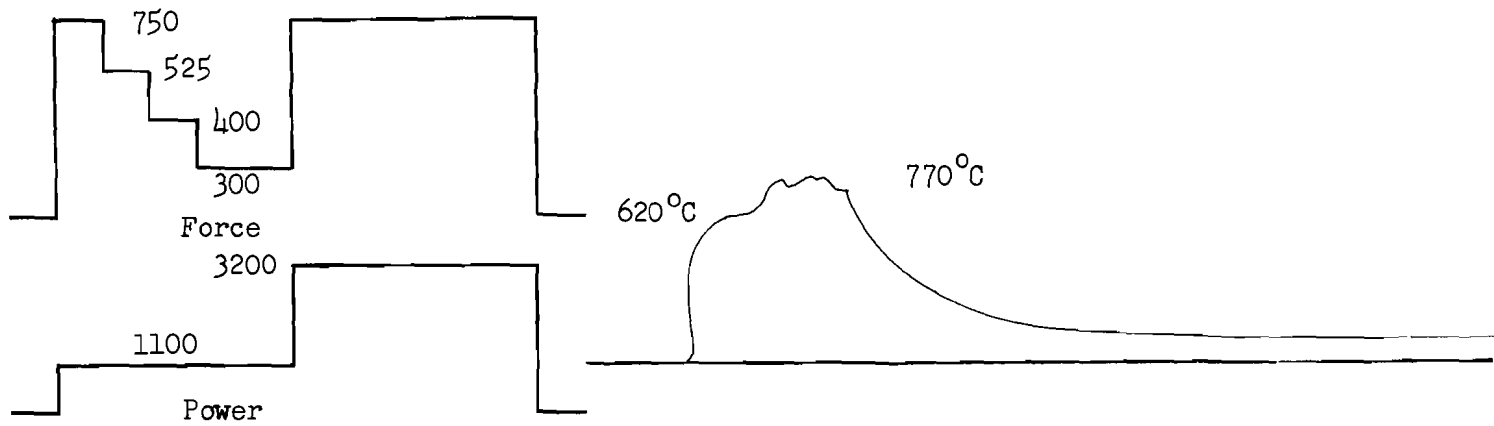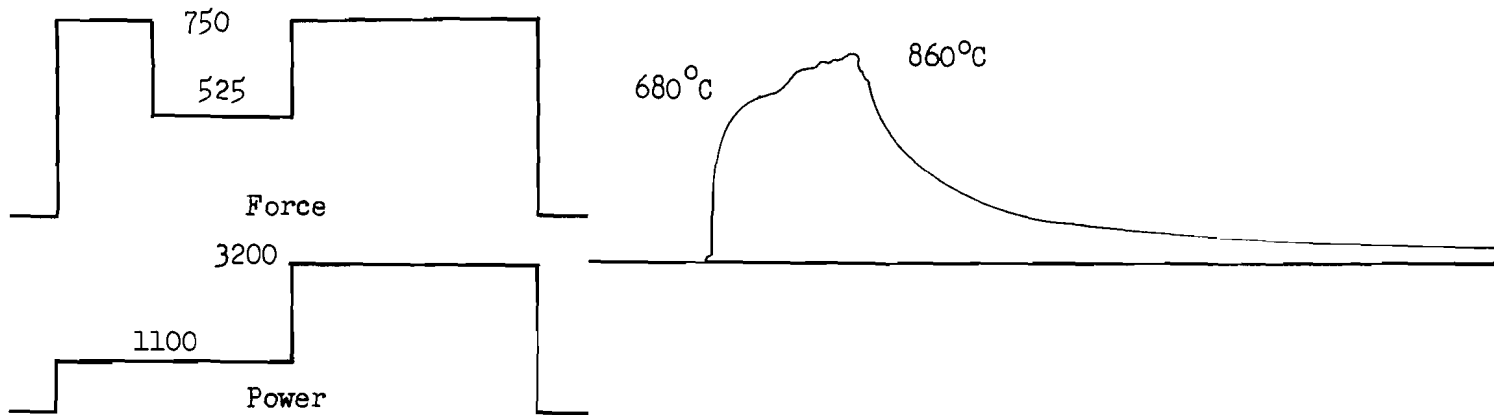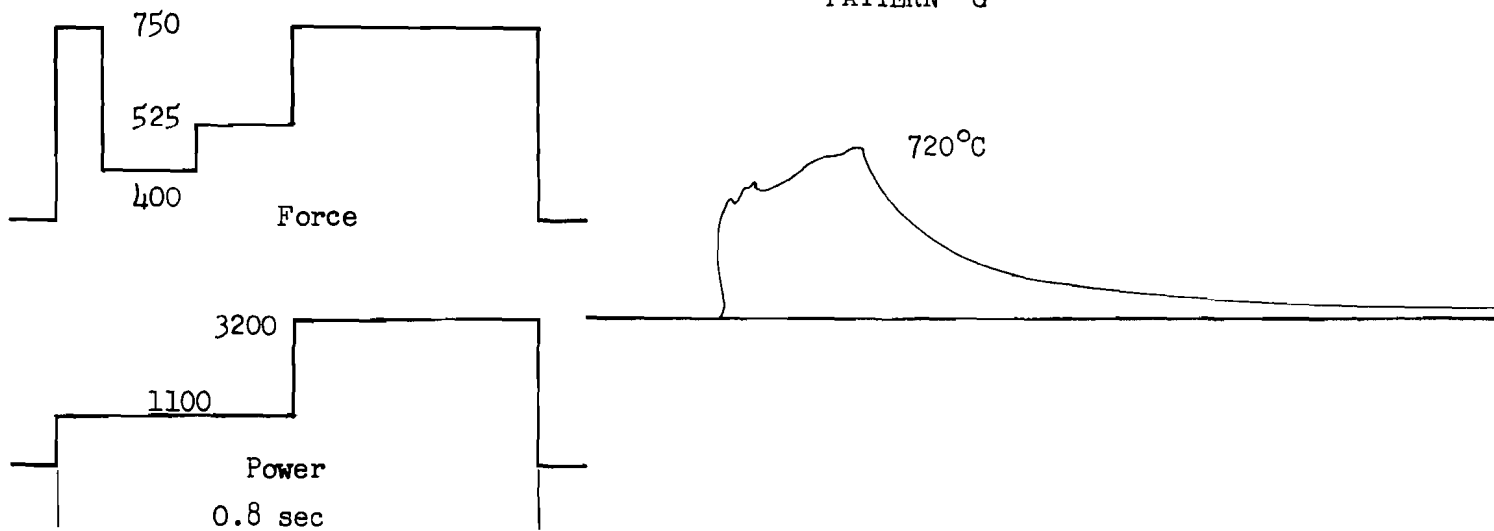
Figure 17

TEMPERATURE TRACES OBTAINED DURING WELDING OF
0.010-INCH MOLYBDENUM-0.5% TITANIUM ALLOY
WITH DIFFERENT POWER-FORCE PROGRAMS

54

PATTERN H

750

Force

3200

1100

Power

800°C

PATTERN I

750

525

Force

3200

1100

Power

720°C

PATTERN J

750

525

Force

3200

2400

Power

0.8 sec

720°C        900°C

Figure 17 (Continued)

750

525

1000

Force

3200

1100

Power

1.9 sec

PATTERN K

830°C
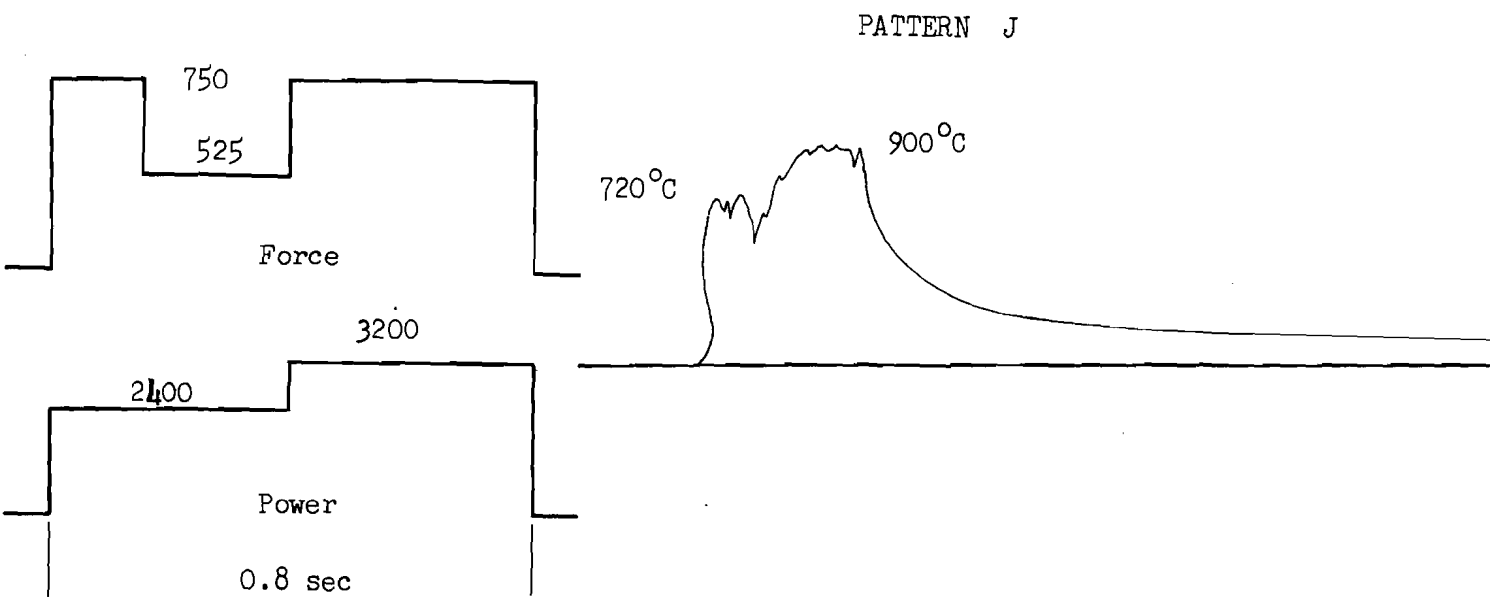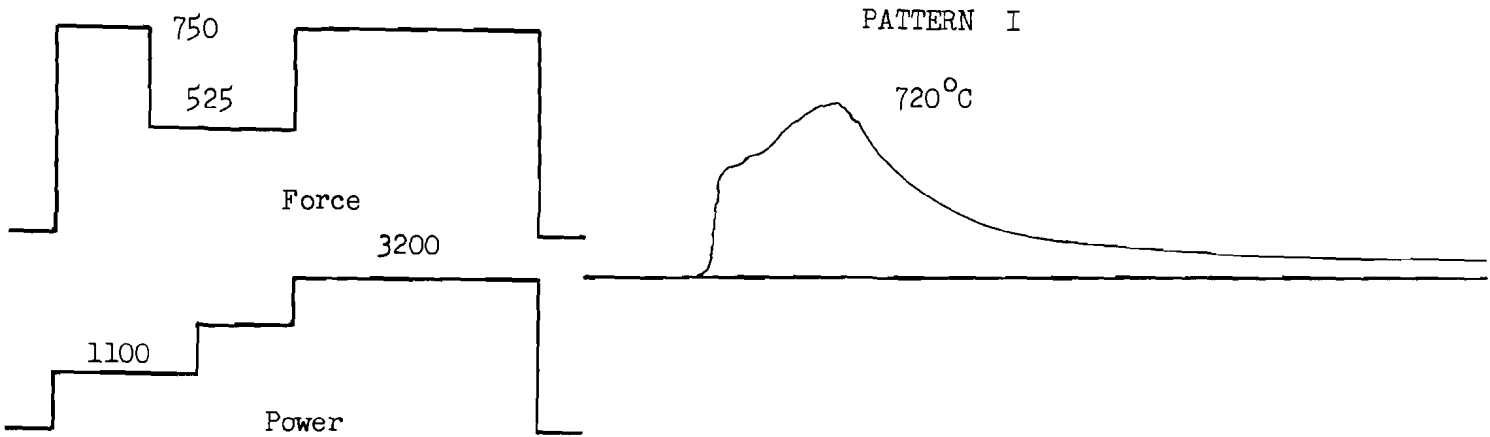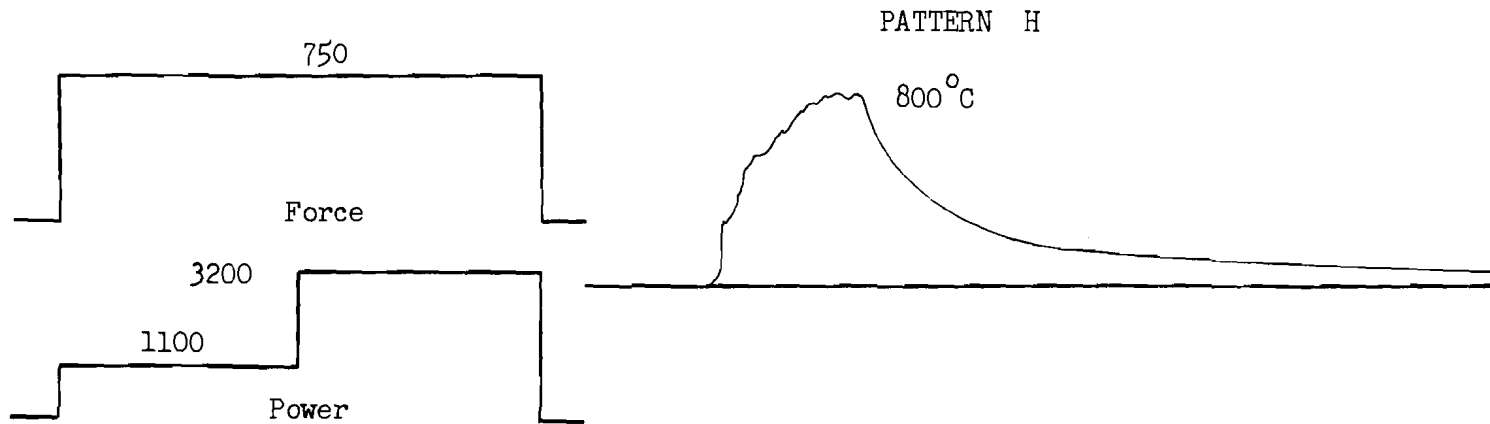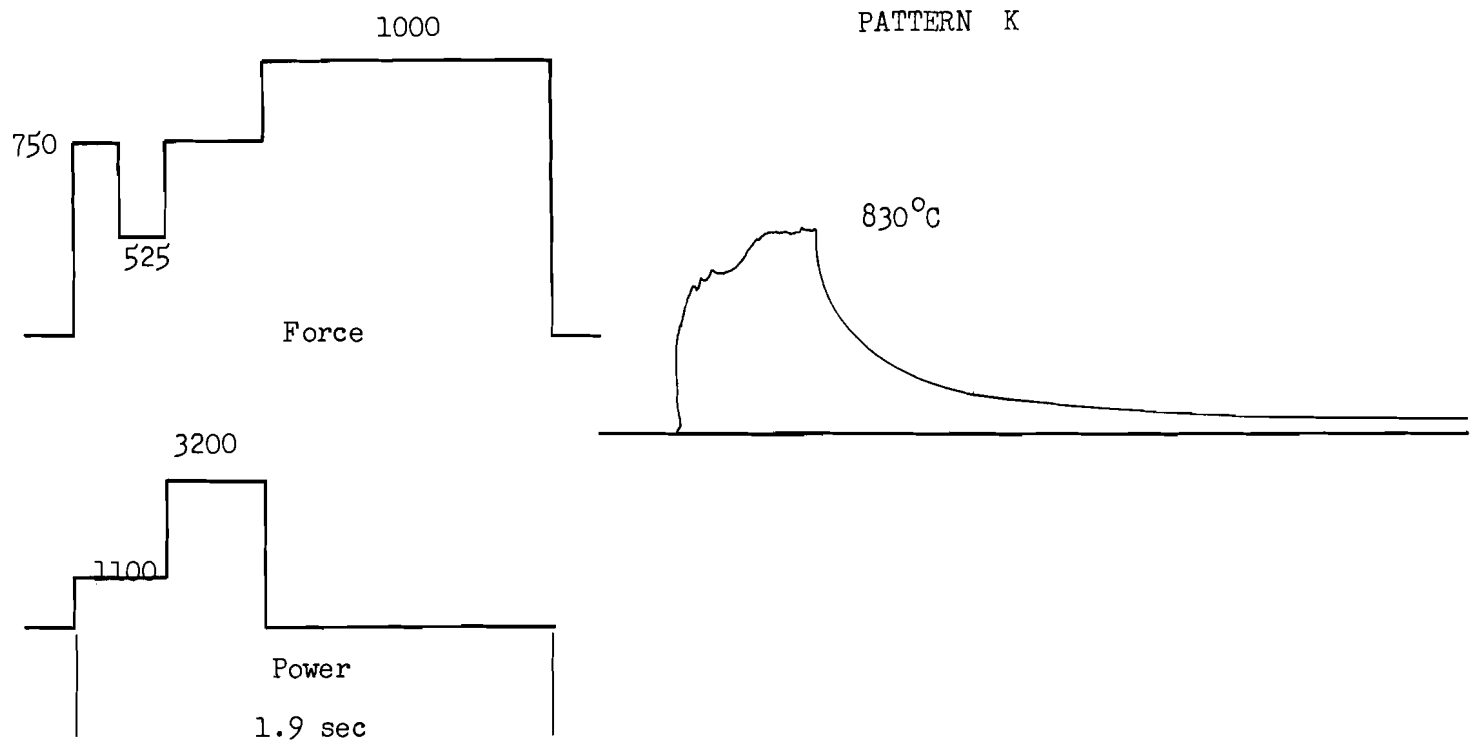
Figure 17 (Concluded)

## VII. WELDING OF MOLYBDENUM-0.5% TITANIUM ALLOY
### WITH POWER-FORCE PROGRAMMING

Substantial effort was devoted to welding molybdenum-0.5% titanium alloy with power-force programming. Much of the work was carried out with the 0.010-inch alloy; some effort was expended with 0.013-inch and 0.020-inch material to ascertain the maximum weldable gage with the PFP-equipped 4-kilowatt welder.

## A. WELDING OF 0.010-INCH MOLYBDENUM ALLOY

### Series 1

The first series of welds for evaluating strength in the 0.010-inch material was made with Patterns A, B, C, and D. Pattern A was modified to reduce power just before the end of the weld cycle, which substantially improved the release of the tip. Another pattern, B', was included to note this reduced power effect with Pattern B. Ten welds were made with each pattern; 8 were tested in tensile shear, and the remaining 2 were examined metallographically.

The power and force values used for each pattern are shown in Table XVI, along with the results of the strength tests. The values shown for "Total Weld Energy" are theoretical values, calculated by integrating under the appropriate Power-Time plots. Statistical analysis of the results is presented in Table XVII.

From a review of the strength values, it is apparent that Pattern C produced the strongest welds. Only one value of the eight was below 100 pounds, and the average was about 25 percent higher than those of the other patterns. The slightly greater total welding energy used for Pattern C might have contributed to the higher strengths. The statistical analysis in Table XVII shows a difference, significant at about a 5% probability level, only between Patterns A and C. Inasmuch as A represents unprogrammed welding, the efficacy of power-force programming with this material seems to be confirmed. The results for B and B' show no significant difference; thus the terminal reduction of power values used for tip release had no apparent effect on weld strength.

### Series 2

The welds involving Patterns A and C were repeated, and Patterns F and K were added for evaluation. The pattern values and results are shown in Table XVIII, and the statistical probability analysis in Table XIX.

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Table XVI

EXPERIMENTAL WELDING OF 0.010-INCH MOLYBDENUM-0.5% TITANIUM

WITH POWER-FORCE PROGRAMMING

(Series 1)

| | PFP Pattern | Total Weld Time, sec | Total Weld Energy, watt-sec | Individual Shear Strengths, pounds | Average Shear Strength, pounds | Standard Deviation, pounds |
|---|---|---|---|---|---|---|
|  | A | 0.5 | 1500 | 52<br>85<br>100<br>147<br>145<br>126<br>30<br>46 | 91 | 46 |
|  | B | 0.5 | 1575 | 37<br>65<br>62<br>62<br>145<br>147<br>65<br>100 | 91 | 27 |
|  | B' | 0.5 | 1500 | 185<br>83<br>73<br>112<br>70<br>90<br>47<br>33 | 99 | 31 |

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Table XVI (Continued)

| | PFP Pattern | Total Weld Time, sec | Total Weld Energy, watt-sec | Individual Shear Strengths, pounds | Average Shear Strength, pounds | Standard Deviation, pounds |
|---|---|---|---|---|---|---|
| Power   C | C | 0.5 | 1640 | 74 | 125 | 26 |
| | | | | 155 | | |
| 3150   3600   .3T | | | | 125 | | |
| | | | | 137 | | |
| | | | | 126 | | |
| 700   850 | | | | 103 | | |
| Force   .3T | | | | 143 | | |
| T=0.5 sec | | | | 137 | | |
| D | D | 0.5 | 1495 | 130 | 95 | 34 |
| | | | | 120 | | |
| 3150   3600   .3T | | | | 92 | | |
| | | | | 55 | | |
| .1T | | | | 141 | | |
| | | | | 64 | | |
| 700   850 | | | | 103 | | |
| .3T | | | | 55 | | |

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Table XVII

STATISTICAL ANALYSIS TO ESTABLISH
WHETHER A SIGNIFICANT DIFFERENCE IN WELD STRENGTH IS OBTAINED
WITH VARIOUS POWER-FORCE PROGRAMS
FOR 0.010-INCH MOLYBDENUM-0.5% TITANIUM ALLOY

(Series 1)

| PFP Pattern | Tensile-Shear Strength, pounds | | No. of Samples | Probability That Variation Is Caused by Chance* | | | |
|---|---|---|---|---|---|---|---|
| | Mean, $\mu$ | Standard Deviation, $\sigma$ | | Comparison With Pattern | | | |
| | | | | A | B | B' | C |
| A | 91 | 46 | 8 | | | | |
| B | 91 | 27 | 8 | > 0.9 | | | |
| B' | 99 | 31 | 8 | > 0.7 | > 0.6 | | |
| C | 125 | 26 | 8 | > 0.05 | > 0.05 | 0.2 | |
| D | 95 | 34 | 8 | > 0.8 | > 0.8 | > 0.8 | > 0.05 |

*
A probability of less than 0.05 indicates a 95% probability that the difference is not due to random variation and is usually considered adequate evidence of significance.

Table XVIII

EXPERIMENTAL WELDING OF 0.010-INCH MOLYBDENUM-0.5% TITANIUM
WITH POWER-FORCE PROGRAMMING
(Series 2)

Power A
3150 —  1650 — .1T
700 —
Force
T=0.5 sec

C
3600
3200 — .3T
700 — 850
.3T

| | PFP Pattern | Total Weld Time, sec | Total Weld Energy, watt-sec | Individual Shear Strengths, pounds | Average Shear Strength, pounds | Standard Deviation, pounds |
|---|---|---|---|---|---|---|
| | A | 0.5 | 1500 | 230 | 102 | 48 |
| | | | | 80 | | |
| | | | | 135 | | |
| | | | | 195 | | |
| | | | | 85 | | |
| | | | | 55 | | |
| | | | | 195 | | |
| | | | | 87 | | |
| | | | | 95 | | |
| | | | | 95 | | |
| | | | | 75 | | |
| | | | | 95 | | |
| | | | | 85 | | |
| | | | | 80 | | |
| | | | | 80 | | |
| | | | | 100 | | |
| | | | | 85 | | |
| | | | | 60 | | |
| | | | | 55 | | |
| | | | | 100 | | |
| | C | 0.5 | 1660 | 95 | 125 | 30 |
| | | | | 155 | | |
| | | | | 115 | | |
| | | | | 115 | | |
| | | | | 105 | | |
| | | | | 155 | | |
| | | | | 180 | | |
| | | | | 100 | | |
| | | | | 105 | | |

Table XVIII (Continued)

| | PFP Pattern | Total Weld Time, sec | Total Weld Energy, watt-sec | Individual Shear Strengths, pounds | Average Shear Strength, pounds | Standard Deviation, pounds |
|---|---|---|---|---|---|---|
| | F | 0.8 | 1720 | 75 | 91 | 39 |
| | | | | 73 | | |
| | | | | 110 | | |
| | | | | 58 | | |
| | | | | 155 | | |
| | | | | 55 | | |
| | | | | 102 | | |
| | | | | 50 | | |
| | | | | 60 | | |
| | | | | 77 | | |
| | | | | 145 | | |
| | | | | 152 | | |
| | | | | 140 | | |
| | | | | 40 | | |
| | | | | 62 | | |
| | | | | 67 | | |
| | | | | 75 | | |
| | | | | 156 | | |
| | | | | 105 | | |
| | | | | 60 | | |
| | K | 1.9 | 1630 | 180 | 93 | 37 |
| | | | | 125 | | |
| | | | | 55 | | |
| | | | | 65 | | |
| | | | | 85 | | |
| | | | | 45 | | |
| | | | | 72 | | |
| | | | | 90 | | |
| | | | | 130 | | |
| | | | | 50 | | |
| | | | | 65 | | |
| | | | | 105 | | |
| | | | | 85 | | |
| | | | | 90 | | |
| | | | | 125 | | |
| | | | | 65 | | |
| | | | | 87 | | |
| | | | | 160 | | |
| | | | | 120 | | |
| | | | | 60 | | |

Power     F

3200
1100
.5T

750
525
Force
.1T   .3T
T=0.8 sec

K

1100
3200
.2T
.2T
.1T
1000
750
550
.1T   .2T
T=1.9 sec

Table XIX

STATISTICAL ANALYSIS TO ESTABLISH
WHETHER A SIGNIFICANT DIFFERENCE IN WELD STRENGTH IS OBTAINED
WITH VARIOUS POWER-FORCE PROGRAMS
FOR 0.010-INCH MOLYBDENUM-0.5% TITANIUM ALLOY
(Series 2 )

| PFP Pattern | Tensile-Shear Strength, pounds | | No. of Samples | Probability That Variation Is Caused by Chance[*] | | |
| | Mean, $\mu$ | Standard Deviation, $\sigma$ | | Comparison With Pattern | | |
| | | | | A | C | F |
|---|---|---|---|---|---|---|
| A | 102 | 48 | 20 | | | |
| C | 125 | 30 | 9 | $> 0.2$ | | |
| F | 91 | 39 | 20 | $> 0.4$ | $< 0.05$ | |
| K | 93 | 37 | 20 | $> 0.5$ | $< 0.05$ | $> 0.8$ |

[*]A probability of less than 0.05 indicates a 95% probability that the difference is not due to random variation and is usually considered adequate evidence of significance.

Again Pattern C yielded greater weld strengths and a lower standard deviation than any of the other patterns, and statistical analysis showed the improvement over F and K to be significant. Reproducibility obtainable with power-force programming is evidenced by the average strength and standard deviation for Pattern C, which are essentially the same as those obtained in Series 1, despite the fact that the welding was performed at a different time and by a different machine operator.

## Series 3

Metallographic studies (described later in this section) of welds made under Series 1 and 2 with 0.5-second weld time revealed that, although superior bonding was obtained with Pattern C, cracking had not been completely and uniformly eliminated. The observed cracks, however, occurred in the metal outside the weld zone.

Experience accumulated in the ultrasonic welding of hard metals such as beryllium has shown that if the clamping force is approximately correct, a most important factor in producing crack-free welds is a short weld time. Accordingly a number of welds were made at a weld time of 0.3 second, with power and force values the same as used in Series 2. Under these conditions the total input energy and weld time were less than those estimated as minimum and it was recognized that welding would be marginal. These welds were examined metallographically and found to have cracks outside the weld zone similar in character to those made in 0.5 second.

Since the cracks were outside the weld zone, it was considered that vibration in the workpieces could be responsible. Accordingly, an experiment was carried out at the 0.3-second weld time, incorporating damping in the area immediately outside the weld area by allowing the sonotrode tip to compress an O-ring (about 3/8-inch diameter) against the workpiece during weld formation.

The experiment was designed to compare Patterns A and C with damping, and Pattern A without damping. The strength data are presented in Table XX and the statistical probability analysis in Table XXI. It is apparent that damping reduced weld strength for both the A and C patterns. The undamped Pattern A welds were significantly superior to both of the damped groups. Strengths for the damped C welds were generally higher than those of the damped A welds, although not on a statistically significant level. It is important, however, that the damped welds made at this shorter weld time for both patterns were entirely crackfree.

No further experimentation along this line was conducted because the supply of 0.010-inch material had been exhausted.

Table XX

EXPERIMENTAL WELDING OF 0.010-INCH MOLYBDENUM-0.5% TITANIUM
WITH POWER-FORCE PROGRAMMING

(Series 3)

Pattern A diagram:
Power: 3150, 1650, .1T
Force: 700, T=0.3 sec

Pattern C diagram:
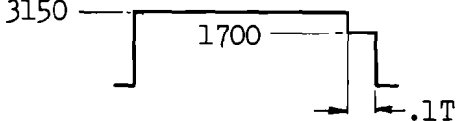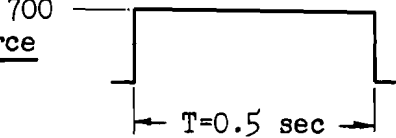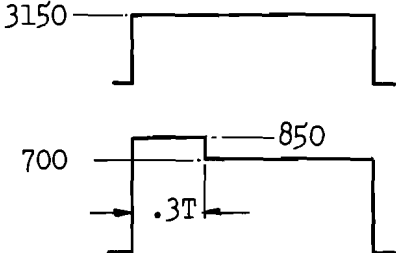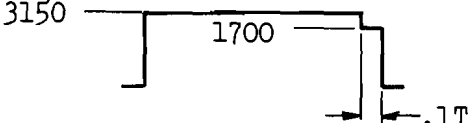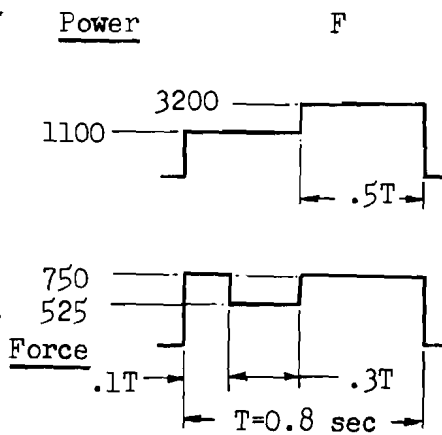Power: 3150, 3600, .3T
Force: 700, 850, .3T

| PFP Pattern | Total Weld Time, sec | Total Weld Energy, watt-sec | Individual Shear Strengths, pounds | Average Shear Strength, pounds | Standard Deviation, pounds |
|---|---|---|---|---|---|
| A | 0.3 | 900 | 110 80 130 112 87 65 65 42 | 86 | 29 |
| A$_{Damped}$* | 0.3 | 900 | 25 25 50 80 40 40 30 30 | 40 | 18 |
| C$_{Damped}$* | 0.3 | 986 | 27 73 82 28 35 50 73 42 | 51 | 22 |

*A neoprene "O" ring surrounded the weld periphery, and the welder clamping force compressed the ring.
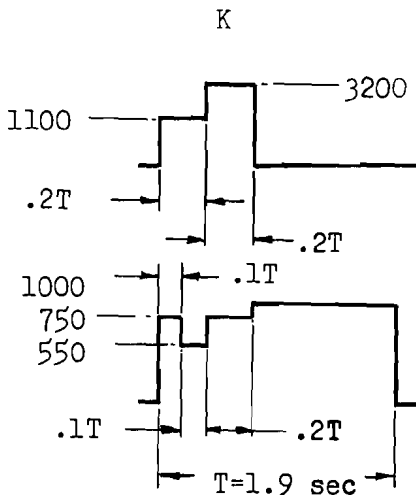
Table XXI

STATISTICAL ANALYSIS TO ESTABLISH
WHETHER A SIGNIFICANT DIFFERENCE IN WELD STRENGTH IS OBTAINED
WITH VARIOUS POWER-FORCE PROGRAMS
FOR 0.010-INCH MOLYBDENUM-0.5% TITANIUM ALLOY
(Series 3)

| PFP Pattern | Tensile-Shear Strength, pounds | | No. of Samples | Probability That Variation Is Caused by Chance* | | |
|---|---|---|---|---|---|---|
| | Mean, $\mu$ | Standard Deviation, $\sigma$ | | Comparison With Pattern | | |
| | | | | A | $A_{Damped}$ | $C_{Damped}$ |
| A | 86 | 29 | 8 | | | |
| $A_{Damped}$ | 40 | 18 | 8 | < 0.01 | | |
| $C_{Damped}$ | 51 | 22 | 8 | < 0.02 | > 0.2 | |

*A probability of less than 0.05 indicates a 95% probability that the difference is not due to random variation and is usually considered adequate evidence of significance.

B.   METALLOGRAPHY OF WELDS IN 0.010-INCH MOLYBDENUM ALLOY

Examination of welds in the 0.010-inch molybdenum-0.5% titanium alloy made at the welding conditions established for the programmed Pattern C and the unprogrammed Pattern A (Series 1 and 2) revealed uniform bonding through the sections.  Cracks within the weld envelope and the spotty bonding characteristics which had been reported in the earlier work were not observed in either group of specimens.  Cracks, however, were observed outside the immediate weld area, usually originating at the inside surface of either or both sheets and propagating in a direction perpendicular to the sheet surface, as shown in Figure 18a and b.  The perpendicular cracks usually terminated in delamination failure within the interior of the sheet.

Subsequent reduction in the weld time from 0.5 to 0.3 second did not eliminate the cracks in either the programmed or unprogrammed weld samples. However, with the damping arrangement described above, crack-free welds were produced with both Patterns A and C at the 0.3-second weld interval. Cracking was observed even with damped welds when the longer weld time was used.  Representative crack-free welds, reproducibly obtained for the first time in this alloy, are shown in Figure 18, c through e, and in Figure 19.

Figure 20 shows planar sections, taken parallel to the sheet surface in the sheet adjacent to the sonotrode tip, of unprogrammed welds made at 0.5 and 0.3 seconds respectively.  The photomicrograph in Figure 20a shows clearly the distribution of cracks around the periphery of the weld zone. Such cracks are absent in Figure 20b, representing a weld made at the shorter weld time.

C.   WELDING OF 0.013-INCH MOLYBDENUM ALLOY

The non-programmed welding machine settings selected for the thicker 0.013-inch molybdenum alloy were 3600 watts power, 700 pounds clamping force, and 0.5-second weld time.  Welds made under these conditions, Pattern A, were compared with those made under Pattern C, since the latter had proved effective in the earlier work.

The tensile-shear strength data obtained with the two patterns are shown in Table XXII.  Pattern C produced welds of 158 pounds average strength, compared with 124 pounds for Pattern A.  As confirmed by statistical analysis, weld strength was improved with the application of power-force programming.

Randomly selected welds in this material were sectioned both parallel (longitudinal) and normal (transverse) to the direction of welding tip displacement, and were examined metallographically.  Representative photomicrographs are shown in Figure 21.  The surface irregularities were caused by a slight amount of tip pickup, although this tip pickup was not sufficient to cause a tip sticking problem.  Occasional redressing of the tip kept sticking to a minimum.
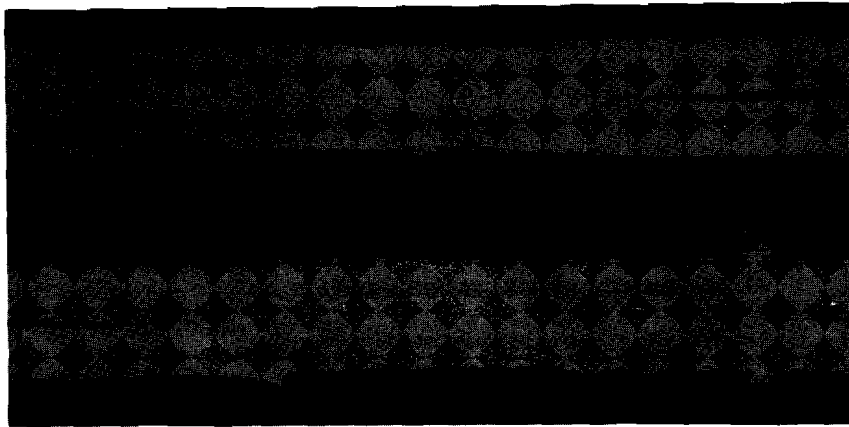
a. Pattern A - 0.5 second

b. Pattern C - 0.5 second
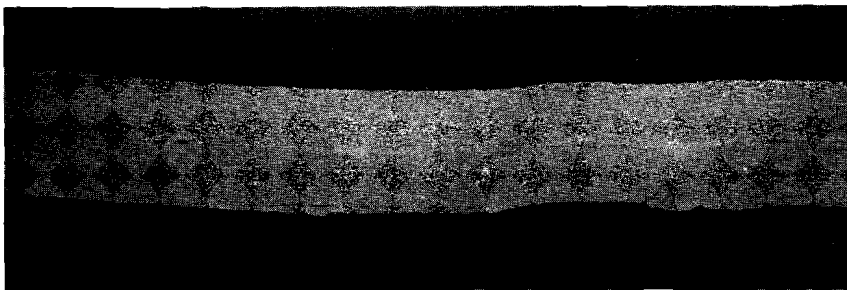
c. Pattern A - 0.3 second

d. Pattern A - 0.3 second
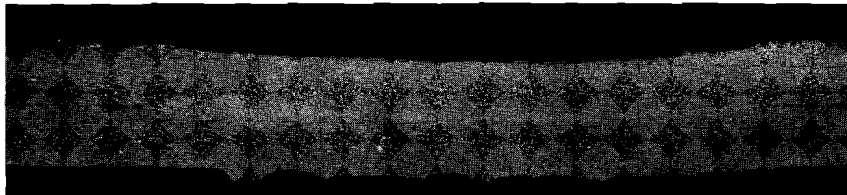
e. Pattern C - 0.3 second

Figure 18

PHOTOMICROGRAPHS OF ULTRASONIC WELDS
IN 0.010-INCH MOLYBDENUM-0.5% TITANIUM ALLOY
(Alkaline Ferricyanide Etch; 30X)
Coupons were damped during welding.
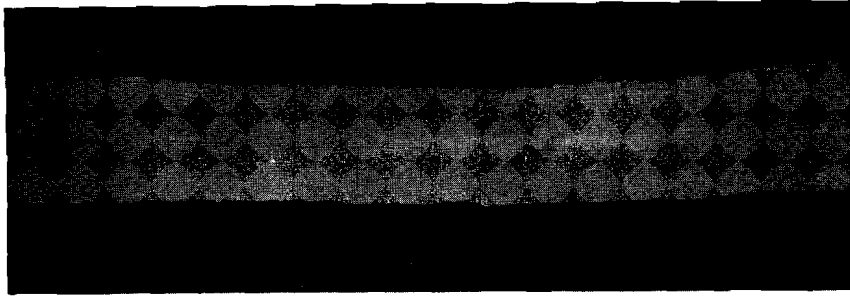
a. Weld at 30X Magnification



b. Portion of Same Weld at 250X

Figure 19

PHOTOMICROGRAPHS OF PFP PATTERN C ULTRASONIC WELD
IN 0.010-INCH MOLYBDENUM-0.5% TITANIUM ALLOY
(Alkaline Ferricyanide Etch)
Weld Time: 0.3 second
Coupons were damped during welding
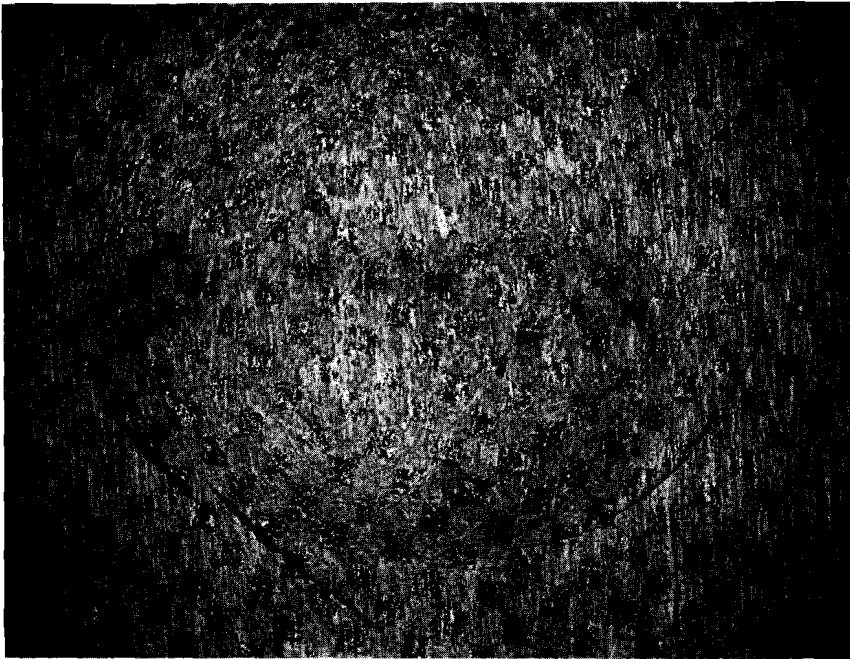
a.   Pattern A
     0.5 second
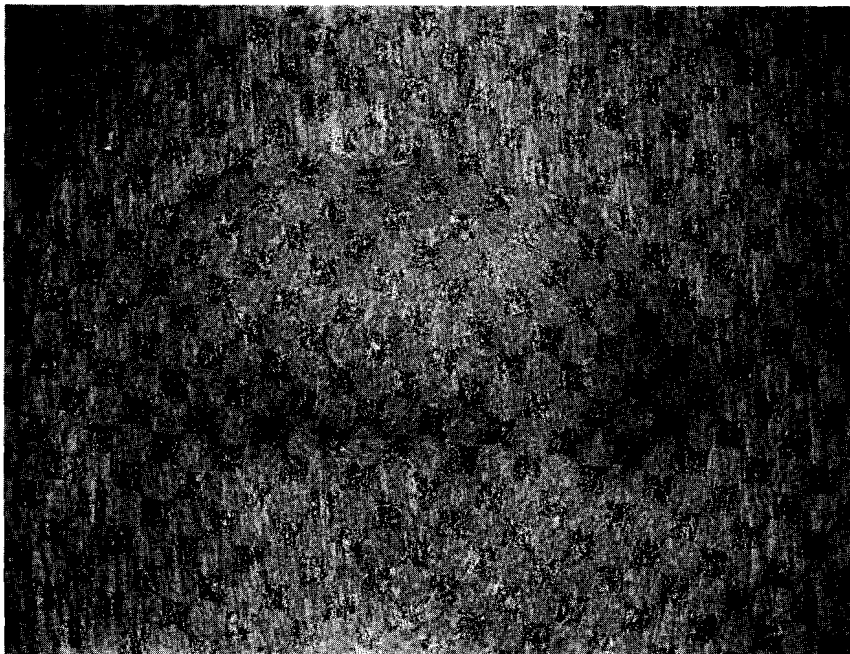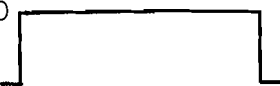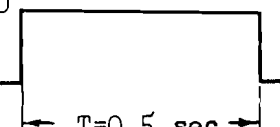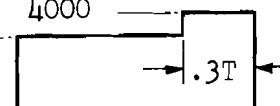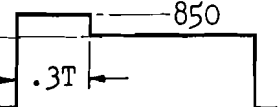


b.   Pattern A
     0.3 second

Figure 20

PLANAR SECTION OF ULTRASONIC WELDS
IN 0.010-INCH MOLYBDENUM-0.5% TITANIUM ALLOY
(Alkaline Ferricyanide Etch; 30X)
Welded with Damping

70

Table XXII

EXPERIMENTAL WELDING OF 0.013-INCH MOLYBDENUM-0.5% TITANIUM
WITH POWER-FORCE PROGRAMMING

| | PFP Pattern | Total Weld Time, sec | Total Weld Energy, watt-sec | Individual Shear Strengths, pounds | | Average Shear Strength, pounds | Standard Deviation, pounds |
|---|---|---|---|---|---|---|---|
| Power 3600 — A (diagram) | A | 0.5 | 1800 | 133 | 151 | 124 | 39 |
| Force 700 (diagram) | | | | 118 | 77 | | |
| T=0.5 sec | | | | 150 | 112 | | |
| | | | | 147 | 158 | | |
| | | | | 155 | 40 | | |
| 4000 C / 3600 .3T (diagram) | C | 0.5 | 1860 | 157 | 172 | 158 | 23 |
| 700 — 850 / .3T (diagram) | | | | 134 | 150 | | |
| | | | | 139 | 164 | | |
| | | | | 210 | 172 | | |
| | | | | 139 | 148 | | |

STATISTICAL ANALYSIS TO ESTABLISH
WHETHER A SIGNIFICANT DIFFERENCE IN WELD STRENGTH IS OBTAINED

| | Tensile-Shear Strength, pounds | | | Probability That Variation Is Caused by Chance[*] | |
|---|---|---|---|---|---|
| | | | | Comparison With Pattern | |
| PFP Pattern | Mean, $\mu$ | Standard Deviation, $\sigma$ | No. of Samples | A | C |
| A | 124 | 39 | 10 | | |
| C | 158 | 23 | 10 | <0.05 | |

[*] A probability of less than 0.05 indicates a 95% probability that the difference is not due to random variation and is usually considered adequate evidence of significance.

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Transverse
Sections (30X)
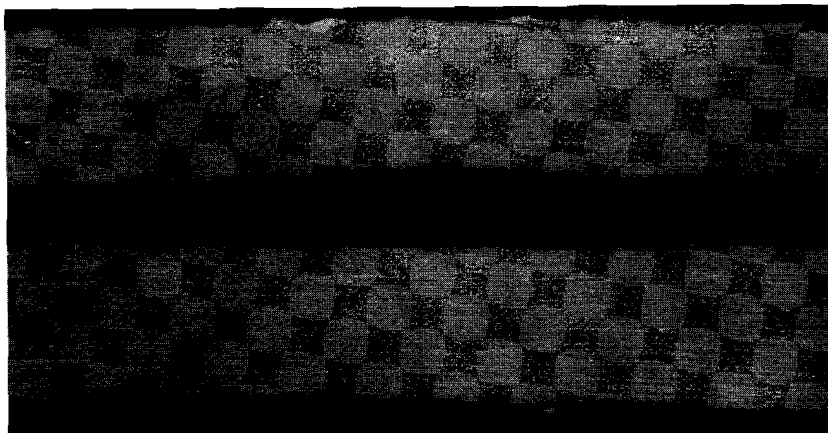
a. Pattern A

b. Pattern C

Longitudinal
Sections
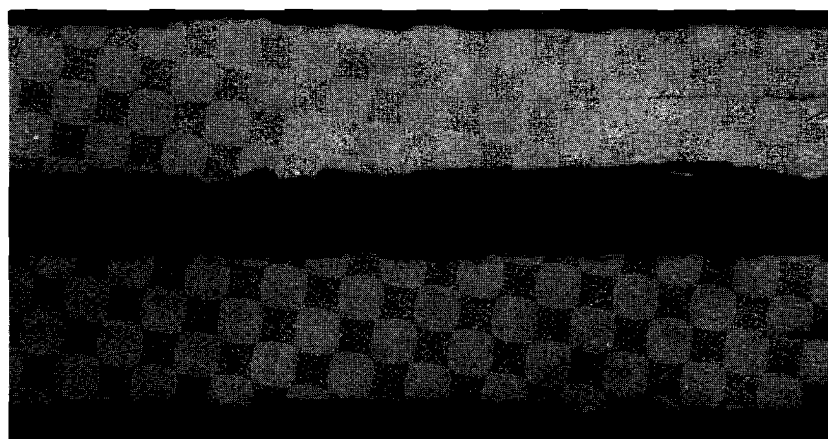
c. Pattern A
(30X)

d. Pattern C
(30X)

e. Pattern A
(200X)

Figure 21

PHOTOMICROGRAPHS OF ULTRASONIC WELDS
IN 0.013-INCH MOLYBDENUM-0.5% TITANIUM ALLOY
(Alkaline Ferricyanide Etch)

In contrast to welds in the 0.010-inch material, these welds in the 0.013-inch alloy were essentially crack-free. None of the specimens examined contained cracks outside the weld zone. In the transverse sections, only one microfissure at the periphery of a weld made with PFP Pattern C was observed. A similar microfissure was observed in a Pattern A weld; however, these Pattern A welds (Figure 21a and c) also showed some delamination within the weld area. The longitudinal sections of both programmed and non-programmed welds showed small edge microfissures.

These "microcracks" in both longitudinal and transverse sections, as shown in Figure 21e, appeared to be a prolongation of the unbonded faying surfaces at the weld periphery. The unbonded edge may have been distorted by the plastic flow at the edge of the weld and directed toward the interior of the sheet, thus creating the internal fissure. The distinction between a microfissure of this type, created by incomplete bonding at the weld periphery, and a true microcrack created by rupture of the metallurgical structure is important in evaluating weld quality.

Both the programmed and non-programmed weld showed uniform bond quality, and no difference in bonding behavior was discernible in the metallographic examination.


## D.    WELDING OF 0.020-INCH MOLYBDENUM ALLOY

The calculated energy requirement for joining the 0.020-inch material (see Section IV and Table VI) was 5000 watt-seconds, which is beyond the capacity of the 4-kilowatt welder with weld times of less than 1.0 second.

A few welds were made to note the effect of weld times of 0.8, 1.0, and 1.5 seconds with unprogrammed welding. At the long weld times, tip sticking became serious. Consequently, two groups of specimens were made with Pattern A modified to provide reduced power just before the end of the weld cycle. Two other groups were made with maximum power output of the equipment and with no variation in either power or clamping force. The patterns and machine settings are shown in Table XXIII, along with the results of shear strength tests. A statistical analysis of the data is presented in Table XXIV.

The average strengths were lower than those obtained with either the 0.010-inch or 0.013-inch material, and standard deviations were high. On a statistical basis, there was no significant difference among the various groups. It was concluded that higher capacity welding equipment would be required to join this thickness of the molybdenum alloy successfully.

Table XXIII

EXPERIMENTAL WELDING OF 0.020-INCH MOLYBDENUM-0.5% TITANIUM
WITH POWER-FORCE PROGRAMMING

| | | PFP Pattern | Total Weld Time, sec | Total Weld Energy, watt-sec | Individual Shear Strengths, pounds | Average Shear Strength, pounds | Standard Deviation, pounds |
|---|---|---|---|---|---|---|---|
| Power | A | A | 1.0 | 3085 | 40 40 45 65 20 70 75 70 60 50 | 53 | 17 |
| | A' | A' | 0.8 | 2468 | 27 40 243 40 | 87 | 103 |
| | Unprogrammed(1) | Unprogrammed 1 | 1.0 | 3900 | 53 75 83 80 70 62 50 90 246 92 | 90 | 57 |

Power
3200 ——
      1600 ——
        .1T
Force
850 ——
  ⊢— T=1.0 sec —⊣

A'
3250 ——
      1600 ——
        .1T
850 ——
  ⊢— T=0.8 sec —⊣

Unprogrammed(1)
3900 ——
850 ——
  ⊢— T=1.0 sec —⊣

74

Table XXIII (Continued)

| | PFP Pattern | Total Weld Time, sec | Total Weld Energy, watt-sec | Individual Shear Strengths, pounds | Average Shear Strength, pounds | Standard Deviation, pounds |
|---|---|---|---|---|---|---|
| Unprogrammed(2)<br><br>4200<br><br>850<br><br>T=1.5 sec | Unpro-grammed 2 | 1.5 | 6300 | 37<br>53<br>92<br>42<br>75<br>71<br>68<br>60<br>98<br>73 | 67 | 20 |

Table XXIV

STATISTICAL ANALYSIS TO ESTABLISH

WHETHER A SIGNIFICANT DIFFERENCE IN WELD STRENGTH IS OBTAINED
WITH VARIOUS POWER-FORCE PROGRAMS
FOR 0.020-INCH MOLYBDENUM-0.5% TITANIUM ALLOY

| PFP Pattern | Tensile-Shear Strength, pounds | | No. of Samples | Probability That Variation Is Caused by Chance[*] | | | |
| | Mean, $\mu$ | Standard Deviation, $\sigma$ | | Comparison With Pattern | | | |
| | | | | A | A' | Unprogrammed 1 | Unprogrammed 2 |
|---|---|---|---|---|---|---|---|
| A | 53 | 17 | 10 | | | | |
| A' | 87 | 103 | 4 | $> 0.3$ | | | |
| Unprogrammed 1 | 90 | 57 | 10 | $> 0.05$ | $> 0.9$ | | |
| Unprogrammed 2 | 67 | 20 | 10 | $> 0.1$ | $> 0.5$ | $> 0.4$ | |

[*] A probability of less than 0.05 indicates a 95% probability that the difference is not due to random variation and is usually considered adequate evidence of significance.

VIII. WELDING OF NIOBIUM ALLOY AND TUNGSTEN
WITH POWER-FORCE PROGRAMMING

The brief experience obtained in the power-force programmed ultrasonic welding of molybdenum-0.5% titanium alloy was applied to the welding of the other two refractory metals: 0.015-inch B-66 niobium alloy and 0.010-inch tungsten. In both cases, welds were made under non-programmed conditions, Pattern A, and under the program of Pattern C.


A. B-66 NIOBIUM ALLOY

The non-programmed machine settings selected for welding the 0.015-inch niobium alloy were 850 pounds clamping force, 3500 watts power, and 0.8-second weld time, for a total energy of 2800 watt-seconds. Preliminary work at these settings indicated that this material responded readily to ultrasonic welding, no cracking was observed, and weld strengths were good.

Table XXV shows the pattern A and C programs selected for welding this alloy and the results of the tensile-shear tests. The application of Pattern C resulted in an average weld strength of 441 pounds, compared to 378 pounds for Pattern A. This difference may be statistically significant, based upon application of small-sample inference methodology.

Thus, with the expenditure of very little effort to arrive at an optimum power-force program, this niobium alloy responded to application of power-force programming by exhibiting an increase in individual weld strength of about 16-17 percent. The slightly greater total energy delivered to the PFP welds (about 5 percent) does not, on the basis of experience, appear to be responsible for the improvement, particularly in view of the fact that in the molybdenum-0.5% titanium alloy welding, some welds obtained with lower total energy using PFP were stronger than other welds made with higher energy and without PFP.

Metallographic examination of several welds made under both Pattern A and Pattern C revealed no evidence of cracks. The photomicrographs of Figure 22 are typical. It was noted that bonding was achieved in random areas within the weld envelope and that deformation and plastic flow at the weld interface were restricted to small areas. Dispersion of the surface films at the interface was thus not altogether complete.

However, the high strengths obtained with these welds indicate that bonding was effective. The use of higher power than was available with the 4-kilowatt welder should effect much improved bonding and possibly higher strengths than those shown in Table XXV.

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Table XXV

EXPERIMENTAL WELDING OF 0.015-INCH B-66 NIOBIUM ALLOY
WITH POWER-FORCE PROGRAMMING

| | PFP Pattern | Total Weld Time, sec | Total Weld Energy, watt-sec | Individual Shear Strengths, pounds | | Average Shear Strength, pounds | Standard Deviation, pounds |
|---|---|---|---|---|---|---|---|
| Power 3500 — 2000 — .1T Force 850 — T=0.8 sec (A) | A | 0.8 | 2680 | 250 305 270 505 470 425 445 345 430 275 | 420 470 475 435 400 420 275 295 275 | 378 | 85 |
| C 4000 — .3T 3500 — 850 — 1000 .3T (C) | B | 0.8 | 2920 | 135 365 525 500 440 460 350 425 470 | 490 425 380 340 575 400 255 525 580 | 441 | 85 |

STATISTICAL ANALYSIS TO ESTABLISH
WHETHER A SIGNIFICANT DIFFERENCE IN WELD STRENGTH IS OBTAINED

| | Tensile-Shear Strength, pounds | | | Probability That Variation Is Caused by Chance[*] Comparison With Pattern | |
|---|---|---|---|---|---|
| PFP Pattern | Mean, $\mu$ | Standard Deviation, $\sigma$ | No. of Samples | A | C |
| A | 378 | 85 | 19 | | |
| C | 441 | 85 | 18 | $< 0.05$ | |

[*] A probability of less than 0.05 indicates a 95% probability that the difference is not due to random variation and is usually considered adequate evidence of significance.
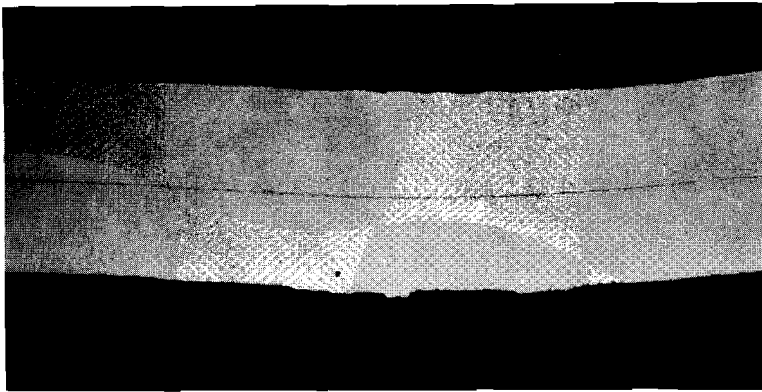
a. Pattern A
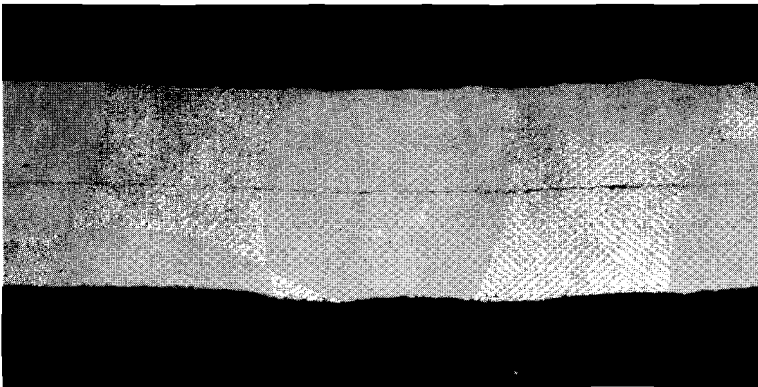


b. Pattern C

Figure 22

PHOTOMICROGRAPHS OF ULTRASONIC WELDS
IN 0.015-INCH B-66 NIOBIUM ALLOY
($HNO_3$ + HF + Lactic Acid Etch; 30X)

## B.   TUNGSTEN

Efforts were made to weld all three of the lots of 0.010-inch tungsten identified in Table IV. Experiments with Lots 6 and 7 were unsuccessful. Cracking and delamination occurred, and the sonotrode tips required frequent redressing and regrinding.

Some degree of success was achieved with Lot 2 material, which was residual from the earlier work. Table XXVI presents the data for strengths of welds made with PFP patterns A and C. In both instances the strengths were low but fairly consistent.

Metallographic examination of the welds made under both conditions revealed only partial bonding and peripheral cracks. The surface of the sheet was distorted, and frequent delamination-type cracks were observed. Although the welds were damped in the same fixture that was used successfully for the molybdenum-0.5% titanium alloy welding, suppression of cracks was not obtained.
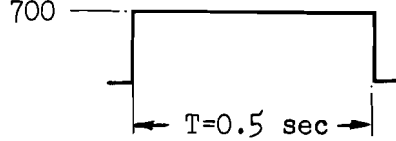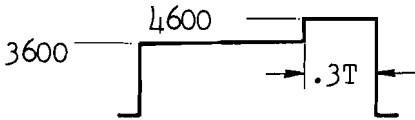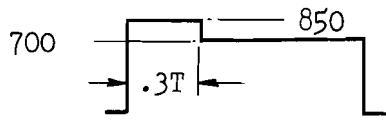
To determine if increased weld energy would improve bonding, a few welds were made without damping at weld times up to 1.5 seconds at maximum available power, but the strengths were in the same range as those obtained at 0.5 second. Reduction of time below 0.5 second was not evaluated because insufficient power was available to produce welds of measurable strength at shorter weld intervals.

It can not be construed from these experiments that tungsten can not be ultrasonically welded. In connection with other work (13) for which a 7.5-kilowatt ultrasonic welder was available, tungsten in gages ranging from 0.015 to 0.030 inch was welded, with strengths up to about 300 pounds.

Higher powers than those available from the 4-kilowatt welder are required for welding tungsten in the short time interval necessary to suppress cracking.

Table XXVI

EXPERIMENTAL WELDING OF 0.010-INCH TUNGSTEN (FANSTEEL)
WITH POWER-FORCE PROGRAMMING
(Damped During Welding)

| | PFP Pattern | Total Weld Time, sec | Total Weld Energy, watt-sec | Individual Shear Strengths, pounds | Average Shear Strength, pounds | Standard Deviation, pounds |
|---|---|---|---|---|---|---|
| | A | 0.5 | 1800 | 43 | 43 | 8 |
| | | | | 30 | | |
| | | | | 40 | | |
| | | | | 44 | | |
| | | | | 38 | | |
| | | | | 47 | | |
| | | | | 58 | | |
| | | | | 52 | | |
| | | | | 35 | | |
| | | | | 45 | | |
| | C | 0.5 | 1860 | 46 | 48 | 10 |
| | | | | 32 | | |
| | | | | 48 | | |
| | | | | 53 | | |
| | | | | 67 | | |
| | | | | 50 | | |
| | | | | 45 | | |
| | | | | 47 | | |
| | | | | 57 | | |
| | | | | 37 | | |

Power    A

3600 —

Force

700 —

|← T=0.5 sec →|

C

4600 —      .3T

3600 —

700 —      850

.3T

81

IX. CONCLUSIONS

1.  Power-force programming controls were devised, assembled into existing ultrasonic welding equipment, and successfully operated.

    a.  Within the limits of the equipment and controls, any pre-set maximum value of either power or force, or both, was divisible into ten increments, and any of the ten such values of either power or force or both could be utilized at any 10-percent increment of the weld time interval.

    b.  The power actually delivered to the transducer and the force actually applied to the welding tip followed their respective pre-set programs with reasonable faithfulness.

2.  On the basis of power and force programs, selected without extensive experimentation, welds in 2024-T3 aluminum alloy and Inconel X-750 exhibited higher strengths than non-programmed welds in these same materials. One series of PFP welds in Type 304 stainless steel exhibited a similar improvement, but these results were not verified in a subsequent series.

3.  Weld-zone temperatures can be substantially affected and controlled by means of power-force programming; thus experience with PFP should permit ultrasonic welding of brittle materials under transiently ductile conditions so that the vibratory stresses associated with the process will not cause material damage.

4.  Based upon the data obtained in this investigation, it appears that power-force programming improves the quality of ultrasonic welds produced in molybdenum-0.5% titanium and B-66 niobium alloys. Conclusive statistical validation of this inference requires larger sample data.

5.  Power-force-programmed ultrasonic welding should be comprehensively investigated as promptly as possible; emphasis should be on correlating weld quality produced under a representative range of power-force programs with specific properties of the materials being welded, such as transient temperatures in the bond zone during welding, brittle: ductile transition temperature, and other material properties.

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APPENDIX A

REVIEW OF PROPERTIES OF REFRACTORY METALS

AND THEIR EFFECTS ON ULTRASONIC WELDABILITY

APPENDIX A

REVIEW OF PROPERTIES OF REFRACTORY METALS

AND THEIR EFFECTS ON ULTRASONIC WELDABILITY

1.  GENERAL FACTORS AFFECTING MATERIAL WELDABILITY

The physical and metallurgical properties of the refractory metals molybdenum, tungsten, niobium, and their diverse alloys must be considered if successful welding is to be effected.  Some properties which influence liquid-phase methods may assume a lesser but still significant position in solid-phase bonding techniques such as ultrasonic welding, while other properties may well be of particular importance in solid-phase bonding.

Weldment material properties which influence ultrasonic welding have not been the subject of research in depth, but experience has indicated that for refractory metals the process is sensitive to metallurgical history.  Since the ultrasonic joining method promotes bonding by localized plastic flow (which may be submicroscopic and appears to be under conditions of triaxial restraint), the thermal and mechanical properties which are determined by the metallurgical consolidation and fabrication procedures seem to be of importance.  The properties considered below are believed significant in connection with the ultrasonic weldability of the refractory metals and alloys.

a.  Fracture Transition

The Group VI-A metals (molybdenum and tungsten) are more susceptible to brittle fracture than the metals of Group V-A (niobium). The latter do not fracture by intercrystalline cracking and are more ductile than the Group VI-A metals at a given temperature.  The effect of solutes on the transition behavior of the Group V-A and VI-A metals has been carefully compiled by Hahn, Gilbert and Jaffee (1).* Mechanical and structural variables have been reported by Seigle and Dickinson (2).

The mechanical factors considered are strain rate and state of stress, deformation velocity, notch effects, surface effects, size effects, and other geometrical and constraint factors.  Structural variables considered are preferred orientation, grain size and shape, and subgrain structure, and include the influence of mechanical working and stress relieving.

The chemical, mechanical and physical factors which influence the transition behavior are intimately associated with the yield and flow

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* Numbers in parentheses refer to References beginning on page A-15.

characteristics of these materials and thus contribute to the ultrasonic weldability of the refractory metals on the hypothesis that ultrasonic welding involves plastic flow at least in some degree. It is beyond the scope of this report to consider these effects in detail, but some of their influence on welding behavior is discussed briefly.

b. Thermal Properties

The significance of thermal conductivity, thermal expansion and heat capacity in the formation of thermal stresses is apparent. The Group VI-A metals have larger thermal conductivity and volume heat capacity than the Group V-A metals. The thermal expansivity is greater in the Group V-A metals. The refractory metals have an affinity for oxygen, hydrogen, and nitrogen and must be protected from the atmosphere at high temperatures. The oxides are volatile at elevated temperatures and are thus non-protective. The volatility of oxides of the refractory metals, particularly molybdenum, can be deleterious to either fusion or solid-phase joining.

c. Variables Related to Method of Fabrication

Much tungsten is produced by powder metallurgy techniques, and pressed and sintered sheet usually has a high interstitial gas content. Molybdenum produced by similar methods also contains high interstitial element concentrations. The influence of interstitial content on raising the transition temperature was mentioned briefly above. Laminations in the sheet resulting from high residual microstresses produce sites for cracking. Arc-cast molybdenum requires rigorous deoxidation. The presence of the molybdenum-molybdenum oxide eutectic results in hot cracking during forging, rolling, or welding. Niobium and its alloys are susceptible to contamination from oxygen, hydrogen, and nitrogen. Control of interstitial content is required to insure ductility during fabrication.

2. WELDING EXPERIENCE WITH MOLYBDENUM-0.5% TITANIUM ALLOY

Weld cracking in molybdenum and its alloys has been reported by various sources. Levy et al.(3,4,5) refer to "catastrophic" cracks which usually start at $45^\circ$ to the rolling direction. Platte(6) reports that cracks were also observed in spot welds at the $45^\circ$ orientation. Welds were made without cracks by TIG methods, while on the same material centerline cracks were obtained with high-voltage electron beam welding.

a. Effects of Contamination on Mechanical Properties

Levy(3) reports a bend transition temperature in molybdenum-0.5% titanium alloy sheet of from about $-20^\circ$ to $500^\circ$F in the "as received" condition and from $-10^\circ$ to $140^\circ$F after removal of surface contamination by grinding.

Although reduction in area of molybdenum-0.5% titanium sheet increases with temperature above the transition temperature, a simultaneous decrease in elongation has been measured(7,8). Observations on the magnitude of this decrease are conflicting. Houck(7) reports maximum elongation of 28% at 200°C, with a decrease to 23% at 600°C. Other reports(8) show an elongation of 35% at room temperature, decreasing to 7% at 800°F, followed by a gradual increase at higher temperatures. These anomalies may be explained by interstitial contamination of the sheet. The effects of contamination on transition temperature and ductility have been reported frequently (3,4,5,6,9,10,11,12).

Hahn et al.(1) report the estimated solubility of the interstitial elements in the Groups V-A and VI-A metals (see Table A-I). As may be seen, the room-temperature solubility in Group VI-A metals is very low. This contrasts with the actual content of interstitials in commercial molybdenum (Table A-II). The effect of oxygen is reported to be more deleterious than that of nitrogen and carbon(1,6,9,10). Kuebrich from General Electric Company(13), however, considers carbides more detrimental to ductility than oxygen or nitrogen.

Although the trend shown by Table A-II is not too obvious, it may be observed that the high-purity molybdenum (No. 1) has a very low transition temperature and that the higher the strain rate the higher the transition temperature. There is also indication that the grain size has a considerable effect on ductility(14).

Oxygen may exist in the molybdenum either as an interstitial element or as molybdenum dioxide ($MoO_2$) or as volatile molybdenum trioxide ($MoO_3$). Molybdenum dioxide has a tendency to precipitate on the grain boundaries(3). There also exists the possibility of $MoO_2$-$MoO_3$ eutectic (melting at 778°C) formation on the grain boundaries(6). This formation has a hot embrittling effect (since the melting temperature of molybdenum is 2620°C), as well as a cold embrittling effect because of the production of a metallurgical notch. As a result, oxygen is particularly detrimental in welding molybdenum and its alloys by conventional processes (using heat), especially if the protective atmosphere is contaminated with this gas(6,9). It should probably also be considered as detrimental in ultrasonic welding.

The surface film on molybdenum and its alloys may be removed by grinding(3,4,5), by chemical etching(6,15), by chemical milling(12), or by electroetching(15). However, according to Weare and Monroe(9), electrolytic etching produces severe grain boundary attack.

The recrystallization of molybdenum-0.5% titanium alloy at 2450°F for 10 minutes in dry hydrogen is a convenient method for measuring the depth of contamination if the cold reduction is about 60 percent(16). Under these conditions, the uncontaminated core material will recrystallize and the contaminated surface will not. However, the recrystallization temperature and time at temperature and the extent of recrystallization depend on many factors,

Table A-I

ESTIMATED SOLUBILITY OF INTERSTITIALS IN REFRACTORY METALS
AT ROOM TEMPERATURE AFTER MODERATE COOLING RATES[1]

| Metal | Interstitial Content, ppm | | | |
|---|---|---|---|---|
| | H | C | N | O |
| Vanadium | 10,000 | 1,000 | 5,000 | 3,000 |
| Niobium | 9,000 | 100 | 300 | 1,000 |
| Tantalum | 4,000 | 70 | 1,000 | 200 |
| Chromium | 0.1-1 | 0.1-1 | 0.1 | 0.1 |
| Molybdenum | 0.1 | 0.1-1 | 1 | 1 |
| Tungsten | N.d.* | 0.1 | 0.1 | 1 |

* N.d. = Not detectable

Table A-II

EFFECT OF INTERSTITIAL CONTENT ON TRANSITION TEMPERATURE
OF MOLYBDENUM PRODUCED BY VARIOUS PROCESSES[1]

| No. | Material | Interstitial Content, ppm | | | | Recrystall. Temp., °C and Time, min | Grain Size No./mm$^2$ | Strain Rate, in/in/sec | Transition Temp., °C * |
|---|---|---|---|---|---|---|---|---|---|
| | | H | C | N | O | | | | |
| 1 | Electron Beam | 1 | 12 | 1 | 1 | | 10 | 3 x 10$^{-4}$ | -269 |
| 2 | Zone Melted | - | 12 | 3 | 5 | | 4000 | 3 x 10$^{-4}$ | -50 |
| 3 | Powder Metallurgy | - | 40 | 41 | 60 | 1150, 30 | 1650 | 3 x 10$^{-4}$ | -40 |
| 4 | Powder Metallurgy 99.9% Purity | - | - | - | - | | 10 | - | 250 |
| 5 | Arc Melted | - | 140 | 56 | 17 | 1150, 60 | 900 | 3 x 10$^{-4}$ | -25 |
| 6 | Arc Melted | - | 140 | 56 | 17 | 1150, 60 | 900 | 2 x 10$^{-1}$ | 40 |

* Temperature where ductility falls below 20% reduction of area in tensile test.

including the percentage of cold reduction, percentage of contaminating elements, etc. Ogden(17) advised that a molybdenum-0.5% titanium alloy sheet should be recrystallized at no less than three temperature levels to find the temperature which will give 75 percent recrystallization of the core; this is considered as the most suitable percentage of recrystallization for estimation of the depth of contamination. Semchyshen et al.(12) give a temperature range from 2300° to 2600°F for 100 percent recrystallization of molybdenum-0.5% titanium alloy sheet with varying carbon content and hardness. National Academy of Sciences reports(18) specify that a correct recrystallization temperature for refractory metals should be the temperature, to the nearest 50°F, which would yield 50 percent recrystallization in one hour.

b.   Effects of Fibrous Structure

Wrought molybdenum shows a fibrous structure which may contain laminations. Levy et al.(3,5) report that laminations are the result of high residual shear stresses, produced by cold rolling. It has been found by this Contractor(19) and other researchers(3) that fibrous material is sensitive to delamination during conventional and ultrasonic welding.

c.   Effect of Notches

Notches in welded molybdenum increase its sensitivity to cracking (3,6,9). The lack of penetration(20) or craters(6) in fusion welds has been reported to be nuclei for cracks.

Cracks (Figure 15 in Ref. 23) or microcracks (Figures 16 and 17 in Ref. 23) have been found around local bonds of ultrasonically welded molybdenum-0.5% titanium. These cracks or microcracks seem to start at the natural notch produced at the edge of the weld interface (Figure 15 in Ref. 23) or where a partial bond is made (Figure 16 in Ref. 23) and where surface contamination may exist.

Levy et al.(3,4,5) and Platte(6) recommend pre-weld and post-weld heating to prevent cracking in fusion and resistance welded molybdenum-0.5% titanium alloy. However, temperatures have to be carefully controlled to produce reliable weldments. Compression stresses applied to the welds have been reported to decrease weld cracking(5). Either pre- or post-heating can probably be provided during ultrasonic welding via power-force programming, and the level of triaxial restraint (compression) can probably also be controlled at least in some modest degree.


3.   WELDING EXPERIENCE WITH NIOBIUM ALLOYS

Niobium and its alloys have recently undergone extensive investigation within this country and abroad, because of the physical properties which make these alloys attractive for many applications within the missile and space industries.

Some important characteristics of niobium and its alloys are listed below:

a. Low thermal-neutron-capture cross section,

b. High melting point and good strength at elevated temperatures,

c. Excellent ductility and fabricability,

d. Refractory properties of its oxide at moderate temperatures,

e. Relatively low density,

f. Freedom from catastrophic oxidation at high temperatures,

g. Good strength (of alloys) at elevated temperature.

As a structural material, niobium has disadvantages for some purposes due to its low modulus of elasticity ($15 \times 10^6$ psi); however, the material can be readily alloyed to improve its strength characteristics. Both molybdenum and titanium form continuous solid solutions with niobium(21), the former being added as a solid-solution strengthener and the latter for increasing the resistance to oxidation at elevated temperatures because of the stability of titanium dioxide(22). The addition of titanium and tantalum also improve the ease with which niobium can be fabricated. Tungsten, molybdenum, vanadium, and hafnium improve high temperature strength. However, molybdenum and tungsten tend to increase the ductile-to-brittle transition temperature. When added in amounts exceeding 1%, titanium decreases transition temperature.

a. Effect of Transition Temperature and Ductility

Niobium and some of its alloys have higher ductility and lower transition temperature when in the cold-reduced condition than in the recrystallized state. D-31 alloy (containing 10% titanium, 10% molybdenum, balance niobium), which was investigated under the previous welding program(23), is ductile to -275°F in the cold-worked and stress-relieved condition. After recrystallization, its transition temperature rises to about 600°F(24).

b. Effect of Contaminants on Material Properties

Interstitial elements (hydrogen, carbon, nitrogen, and oxygen) have a considerable effect on the brittle-to-ductile transition temperature of niobium and its alloys. Researchers, however, do not agree on the magnitude of the effect. It has been reported(25) that, while nitrogen has little effect, oxygen has a very detrimental effect on ductility, especially with the D-31 alloy. After exposing D-31 alloy for 4 hours at 1800°F in an argon atmosphere containing oxygen, the microhardness at the surface was reported(25) to increase sharply in relation to that in the center (about 700 Knoop at 0.001 inch from the surface as opposed to about 250 Knoop in the center). This phenomenon was attributed to a low diffusion rate of oxygen in D-31 alloys, compared with the rates in other niobium alloys which do not exhibit this tendency.

While some Russian investigators are agreed that oxygen has the more detrimental effect, nitrogen is considered by most American researchers (1,6,16,24,28) to be more detrimental. To substantiate this hypothesis, it is cited(28) that 0.63% of oxygen in an argon protective atmosphere effects a 77°F rise in the transition temperature, while the same amount of nitrogen would increase the transition temperature by 482°F. Nitrogen has also been noted to cause an increase in surface hardness(24,26). According to Zakharova et al.(27), nitrogen precipitates from solid solution as nitrides during aging of unalloyed niobium at a temperature between 100° and 500°C. The surface hardness and the hardness at the core decrease considerably.

Carbides, which precipitate uniformly within the grains rather than on the grain boundaries, decrease elongation, reduction in area, and ultimate tensile strength. Carbides have a high melting temperature (3500° ± 125°C) and are difficult to dissolve.

The mechanical and physical properties of recrystallized D-31 alloy are apparently more affected by contaminants than those of the cold-reduced material(7). In a pilot production of wrought D-31 alloy, a transition temperature of 200°F was found, while the recrystallized material showed a transition temperature of 450°F. The transition temperature for the wrought alloy with 400 ppm interstitial content was 200°F; with 1200 ppm interstitial content, it rose to 1200°F.

c.  Effect of Contaminants in Fusion and Resistance Welding

D-31 alloy was observed to crack when fusion welded by the TIG process in a helium-filled chamber(6,29). In this case the ductile-to-brittle temperature was near 600°F. When the material was welded in open atmosphere with only the protecting trailing shield, the transition temperature approached 800°F. This cracking tendency under similar conditions has been reported by others(24,28). The cracks were attributed to interstitials during welding, with subsequent precipitation on the grain boundaries. In addition, an increase in hardness occurred even though nitrogen could not be detected by mass spectrometry(6). Cracking also persisted during resistance spot welding of niobium alloys(6), and heavy electrode tip sticking was encountered. The cracks propagated through the welds at 45° to the original rolling direction, and the heat-affected zone was very brittle.

It is not known how much interstitial content can be tolerated to avoid weld embrittlement during fusion welding of niobium alloys. It has been postulated(30) that not only should the level of specific contaminants be controlled, but the combined concentration of the three interstitial elements, carbon, nitrogen, and oxygen, should not exceed 700 ppm. However, carbon content in D-31 alloy sheets used by this Contractor in previous studies(23) was as high as 1100-1200 ppm.

There is little information in the literature on the effect of hydrogen and carbon on D-31 alloy welded by conventional methods. Although

the solubility of hydrogen in unalloyed niobium is reported to be 9000 ppm(1), even much lower hydrogen content seems to have a detrimental effect on the transition temperature of this metal. The solubility of carbon in niobium at room temperature is reported to be 100 ppm(1).

The higher the speed of welding, the less opportunity for contamination and for precipitation. It has been found(24,28), however, in welding D-31 alloy with the electron beam method, that although the transition temperature is slightly improved with increased speed, the reverse occurs when TIG welding is performed in a chamber. The same investigators also reported more micro-fissures present when welding was carried out at 36 inches per minute than at 15 inches per minute.

d.  Effect of Pre-Weld and Post-Weld Heating

It has been found(24,28) that no lowering of the transition temperature occurs when D-31 alloy is preheated to 500°F prior to welding. The transition temperature can be lowered by about 100-150°F, however, by heating the alloy for 24 hours or longer at 2100°F. After the post-weld heat treatment, the continuous grain boundary precipitates in the fusion and heat-affected zones were observed to be dispersed, and massive particles, suspected to be carbides, were formed. This suggests that over-aging takes place during the post-weld heating.

e.  Ultrasonic Welding of D-31 Alloy

As reported previously(23), initial attempts by this Contractor to weld D-31 alloy were not successful. The bonding was inconsistent (Figure 20 in Ref. 23), and the tensile-shear strengths were erratic. Considerable improvement was shown with the Lot 4 material (Table X in Ref. 23). Metallurgical bonding was good (Figure 26 in Ref. 23), and tensile-shear strengths were satisfactory. Cracking was experienced only when the clamping force was too low (below that indicated by the threshold curves), or when the surface of the alloy or the sonotrode tip was contaminated with foreign particles.

f.  Ultrasonic Welding of B-66 Alloy

Little technical information is available on the B-66 niobium alloy, which has a composition of 5% molybdenum, 5% vanadium, 1% zirconium, balance niobium. One may assume that some of the general comments on niobium contained above would also apply to the B-66 alloy.

This Contractor has had previous exploratory welding experience with cold-rolled and stress-relieved 0.006-inch B-66 alloy foil (detailed processing history unknown). The results are given in Table A-III. Although welds with niobium foil interleaves were weaker than those without the foil interleaves, the latter were more consistent and produced less tip sticking. Metallographic analysis indicated that joints made by overlapping spot welds should be helium tight. No cracking was experienced.

Table A-III

PRELIMINARY DATA ON ULTRASONIC SPOT-TYPE WELDS

IN COLD-ROLLED, STRESS-RELIEVED 0.006-INCH B-66 NIOBIUM ALLOY

| No. | Welding | | No. of Specimens | Tensile-Shear Strength, pounds | | Comments |
| | Method | Foil Interleaf* | | Mean | Standard Deviation | |
|---|---|---|---|---|---|---|
| 1 | Single Spot | No | 11 | 112 per spot | 48 | Joints were spotty, tip sticking, broken by shear. |
| 2 | Single Spot | Yes | 11 | 94 per spot | 32 | Improved joints, no tip sticking, broken by shear. |
| 3 | Overlapping Spot** | No | 12 | 366 per 3/4" | 86 | Joints were spotty, no tip sticking, failure at weld line. |
| 4 | Overlapping Spot** | Yes | 4 | 338 per 3/4" | 81 | Joints were more continuous, no tip sticking, failure at weld line. |

*  0.0005-inch niobium foil.

** 3/32-inch spacing, 1/32-inch overlap.

In the studies made in this program, recrystallized B-66 niobium alloy was used because the producer (Westinghouse) advised that recent tests had shown the recrystallized condition to provide better ductility than the cold-rolled condition(31).

## 4. WELDING EXPERIENCE WITH TUNGSTEN

### a. Transition Temperature and Ductility

Similar to molybdenum and its alloys, wrought tungsten possesses much lower transition temperatures than the recrystallized metal. For example, in wrought commercial purity tungsten sheet, the transition from ductile (zero t bend) to brittle (71$\frac{1}{2}$ t bend) occurs in the temperature range from $345^\circ$ to $390^\circ F$; in recrystallized sheet, the temperature ranges from $570^\circ$ to $615^\circ F$(10).

### b. Effect of Contamination

Single crystals of tungsten, even with a high impurity content, exhibit good ductility at temperatures as low as $-100^\circ C$, whereas polycrystalline metal at room temperature is very brittle(32). When from 2 to 20 ppm of oxygen were added to single-crystal tungsten, the transition temperature reportedly(33) increased from $0^\circ$ to $80^\circ F$; however, when 4 to 10 ppm of oxygen were added to the polycrystalline metal, the transition temperature increased from $450^\circ$ to $660^\circ F$. The same investigator found that grain size is not a contributing factor in the transition temperature range.

In Table A-I are tabulated the interstitial contents likely to be maintained in tungsten in solid solution after moderate cooling rates as compared to those usually found in commercially available metal(1). Because of the difference in the room-temperature solubility and the actual content, the interstitials diffuse toward the grain boundaries and thus produce serious embrittlement with a tendency to grain boundary cracking. Oxygen seems to have the most detrimental effect on ductility. Embrittlement has also been explained as the result of metallic surface impurities, such as iron, chromium, calcium, and nickel(13).

### c. Effect of Surface Condition

Embrittlement has also been related to surface conditions, such as mechanical surface notches. By electropolishing tungsten wires, it has been reported(34) that strength was improved by as much as 30 percent. Another researcher(35) noted a similar improvement in ductility. The use of electro-polishing to remove 0.005 inch from the diameter of certain tungsten wire increased its bend ductility as much as sevenfold; neither grinding nor abrading improved the ductility of the wire. It has also been reported(32) that cracks apparently started on the grain boundaries beneath the surface of recrystallized and electropolished tungsten sheet, indicating that perhaps not only mechanical notches but also grain boundary conditions are detrimental.

The same investigator reported the presence of irregular but generally circular elevation on the surface of powder metallurgy tungsten sheet in the "as rolled" condition. With Knoop hardness measurements, these elevations showed hardness 200 to 300 points higher than the average hardness of the surrounding areas (Knoop 451), and lattice parameters of 3.1596 Å as opposed to 3.1586 Å in the softer areas. By removing 0.002-inch by electropolishing, the elevations were not completely removed, but the lattice parameters of both areas were decreased to 3.1583 Å. It seems that the increase in hardness of these elevations might be due to the strain produced by lattice distortion, which, in turn, is caused by interstitial contamination.

This Contractor's experience has demonstrated that the removal of about 0.005-inch from the diameter of tungsten wire and about 0.002-inch from the surface of tungsten sheet improves the bend ductility of the wire and considerably improves ultrasonic weldability(19).

d.   Effect of Strain Rate

Commercially pure tungsten sheet exhibits 20 percent reduction in area (used as a criterion of transition temperature) at 300°F with a corresponding strain rate of 0.05-inch per inch per minute. The same reduction in area will occur at about 530° and 700°F at strain rates of 100 and 19,000-inches per inch per minute respectively(10).

e.   Effect of Alloying

Alloying may increase the ductility of tungsten, and rhenium is one of the best alloying elements for this purpose. Rhenium additions affect the properties of tungsten as follows:

(1)   Room-temperature and elevated temperature strengths are increased.

(2)   Electrical resistivity is increased by 14 percent with the addition of 3% rhenium.

(3)   Lower ductility and decreased transition temperatures occur even after recrystallization, to a maximum of about 26 weight percent of rhenium.

Table A-IV presents the results of a crude comparative bend test with tungsten and tungsten-rhenium alloy. From these data, the superior ductility of tungsten-rhenium wire is evident.

f.   Chemical Reactivity

During the ultrasonic welding of tungsten, the weld area appears to achieve a high temperature around the welding tip. Atmospheric nitrogen has no effect on tungsten, but oxidation of this metal, although not as severe as

Table A-IV

COMPARATIVE ROOM-TEMPERATURE BEND DUCTILITY
OF 0.060-INCH TUNGSTEN WIRES

Bend Radius Approximately 2D

| Material | Bend Angle, degrees | Results |
|---|---|---|
| Tungsten, as received, stress relieved | 10 | Brittle fracture |
| Tungsten, stress relieved at $1100^{\circ}F$, electropolished, 0.005-inch removed by electropolishing | 30 | Brittle fracture |
| Tungsten-3% Rhenium, as received | 180 | No cracks |

that of molybdenum, is a concern at elevated temperatures. Unfortunately, all available data on the oxidation of tungsten are given for exposure times in hours or minutes, while in ultrasonic welding the exposure amounts to only a fraction of a second.

Tungsten does not oxidize in dry air up to 300°C; between 300° and 700°C, oxidation is insignificant(36). However, moisture in the air accelerates the formation of oxides. Oxidation in air increases with an accelerated rate with increasing temperature, reaching catastrophic rates at about 1200°C.

The oxidation of tungsten occurs progressively as follows:

| Oxide | Color | Formation Temperature, °C |
|---|---|---|
| WO | Gray | Low |
| $WO_2$ | Brown | Above 400 |
| $W_2O_3$ | Blue | 400-700 |
| $WO_3$ | Yellow | Above 700 |

The blue oxide ($W_2O_3$) forms a very adherent film. However, above 700°C its thickness gradually diminishes and a loose powdery $WO_3$ is formed; this disappears at about 1100°C. $WO_3$ sublimates in air above 1200°C. It melts at 1473°C, and its volatilization above 1750°C is very rapid.

In addition, the following colors of oxides have been reported(36), depending on oxygen pressure: violet, red-violet, blue-black, black with green edges, blue-black with greenish-yellowish edges, yellow-black, etc.

It has been observed during other studies(19) that tungsten wire achieves a high local temperature when ultrasonically welded to hard dissimilar metals. In some combinations distinct heat tint is formed, probably due to oxides of tungsten. It is not known if these oxides are formed directly during welding or if they are produced by vapor deposition. However, a yellow tint, when observed, is invariably located on the side of the weld adjacent to the anvil. It has been tentatively concluded that this tint is produced by $WO_3$, evaporated and subsequently deposited on the colder area of the coupon or wire. This would also indicate that the local temperature reached during welding is above 1750°C.

It was generally found that the tint was present when unsatisfactory welds were obtained between tungsten wire and dissimilar-metal coupons

or between tungsten coupons and dissimilar-metal wires. If the weld was satis-factory, the materials showed very insignificant or no tint.

Therefore, it has been tentatively concluded that: (1) tint appears to be associated with the quality of the joint; (2) the relative absence of the tint on plates and wires when satisfactory welds were obtained seems to indicate that friction on the weld interface without welding is the cause of the tint oxidation; and (3) at least some oxide probably evaporates from the interface and is subsequently deposited on the colder area of the plate.

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APPENDIX B

PROGRAM PLANNING AND MONITORING

# APPENDIX B

## PROGRAM PLANNING AND MONITORING

Promptly after initiation of the technical effort on this program, a meeting was held by our engineering staff and representatives of the Office of Naval Material, Reading, Pennsylvania, who monitored this program for the Bureau of Naval Weapons contracting office.

At that time, the inspector for the Office of Naval Materials prescribed a graphic technique for scheduling and monitoring the essential elements of this program in accordance with the Department communique "Line of Balance Technology," NAVEXOS P1851 (Rev 4-62).

Development scheduling was planned for completion of the program within the allotted contract time. The contract was dated August 16, 1962, but was not received until November 27, 1962 and, in spite of efforts to accelerate the completion of the technical phases, the originally projected twelve full months of effort were required. Those phases which overran the anticipated completion dates as related to the contract execution date of August 16, 1962 are indicated in the attached Program Plan Chart by dotted lines.

At the request of the Office of Naval Material, the Program Plan initially agreed upon was later condensed (from 16 phases to 10) and was followed through as indicated on the chart.

LEGEND

⬡ Engineering and Development

◯ Purchase Parts

▢ System Use and Evaluation

Open symbol indicates start of phase.

Line-shaded symbol indicates completion.

1. Preliminary Engineer-
   ing and Tentative Equip-
   ment Specifications

2. Components and Material
   Procurement

3. Establish Material
   Specifications

4. System Development

5. Establish Welder
   Settings

6. Metallography, Welding
   and Evaluation:  Mo-0.5 Ti

7. Metallography, Welding
   and Evaluation:  Control
   Materials

8. Metallography, Welding
   and Evaluation:  Selected
   Refractory Metals

9. Establish Optimum
   Welder Settings

10. Reports
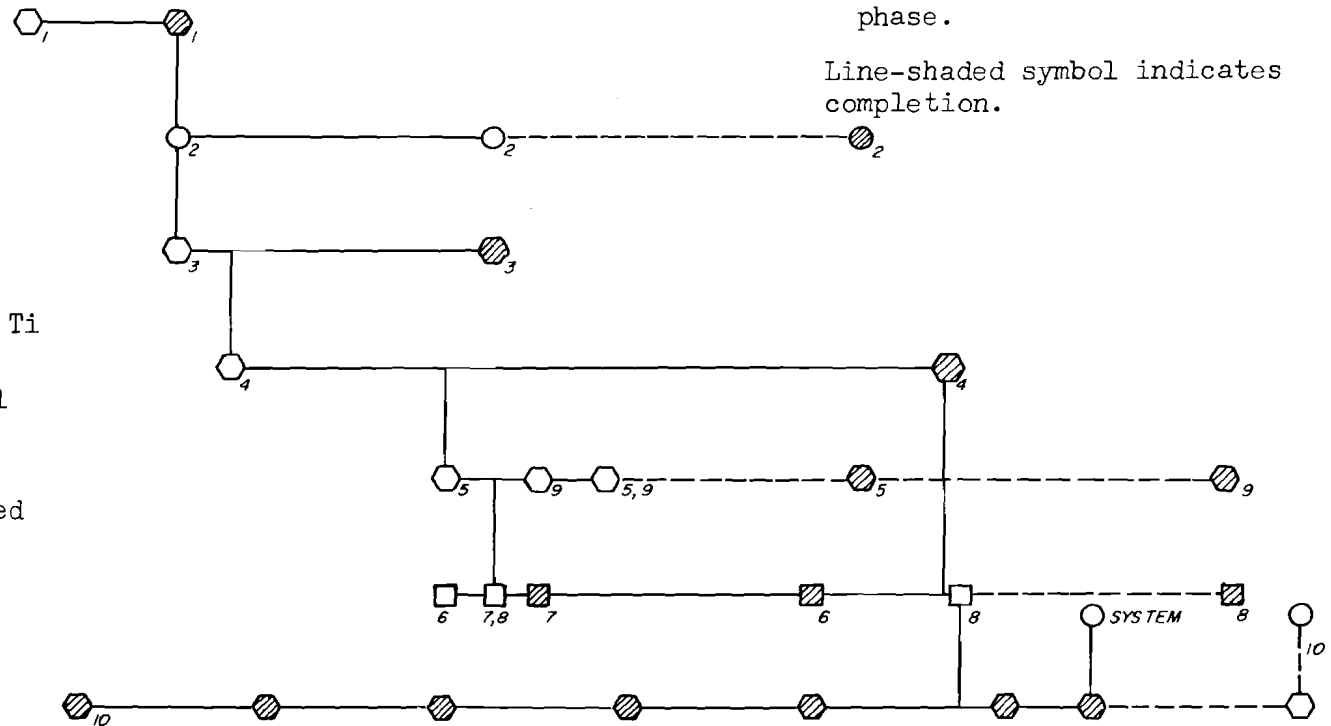
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PROGRAM PLAN CHART

INVESTIGATION OF ULTRASONIC WELDING OF REFRACTORY METALS WITH POWER-FORCE PROGRAMMING

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